FAULTS AND FAILURES IN ELECTRICAL PLANT

CAUSES AND RESULTS CURE AND PREVENTION

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PREFACE

ELECTRICAL engineering literature to-day does not, as a rule, provide the reader with much information dealing with practical experience. The innumerable books published offer to the student and the practising engineer sound information for the theoretical solution of his problems, but they tend to give too little attention to those problems, encountered during the manufacture and operation of electrical machines and apparatus, which can be briefly described as "troubles."

Unfortunately most firms and individuals keep their mistakes and breakdowns to themselves, and this tends to prevent publications from being as interesting and instructive as they might be to erection engineers, designers, and works managers. On this account, it was decided to experiment with a new method of approach which may be called "a treatise on troubles."

The result of the experiment, this book, will therefore describe phenomena arising during testing, assembling, putting into service, and more particularly the experience gained in connection with the maintenance and repair of plant which has given trouble. The actual breakdown is made the principal point in every case and its causes, progress and results are described as clearly as possible. Afterwards those methods of treatment are described which can be carried out on site. Methods which are only practicable in the suppliers' factory are not included. The same applies to measurements necessary when testing for faults. Special meters and the auxiliary devices of the works electrical test are assumed not to be available. A brief mention is made, however, of those which facilitate efficient maintenance and operation as well as reconstruction. It is assumed that the reader is familiar with the general theories on which machines, apparatus, and installations are designed, as well as their construction and method of operation, or that he will make himself acquainted with them from a textbook. Only in a few important cases is the complete theoretical or physical basis discussed.

The scope of the book has been limited to heavy current machines, apparatus and plant, which of course, automatically

excludes certain important types of trouble. Even as it is, the material available has had to be drastically curtailed.

To obtain actual personal experiences of faults in the different sections, the co-operation of specialists in the various types of machines has been obtained.

These collaborators include Herr H. Knöpfel for Part 1 ("Electrical Machines") assisted by Herr F. Roggen for Chapter VI on "Vibration"; Herr A. Meyerhans for Part 2 ("Transformers") and Herr R. Keller for Part 3 ("Apparatus"). Dr. H. Stäger dealt with the troubles arising in materials in Part 4, which are rather exceptional due to their physico-chemical nature.

The contributions of these collaborators were arranged and expanded by the author and made uniform with the remainder of the book as regards method of description and diagrams.

The author's best thanks are due to the Brown Boveri Co. of Baden and particularly their technical director, Herr M. Schiesser. His inspiring reception of the proposals and permission to carry them out were important factors in bringing the book to completion. In addition, thanks are due to the Brown Boveri Co. for enabling the collaborators to provide their contributions as well as facilitating the work in every way.

Thanks are also due to the author's fellow workers here for their zealous and persevering share in the whole undertaking.

ROBERT SPIESER

WINTERTHUR, *August*, 1932

FOREWORD TO THE ENGLISH EDITION

DEVELOPMENT and progress in electrical machinery usually take place by two quite distinct processes. In the one case, there is the application of fundamental scientific laws in the study of electrotechnical and mechanical problems, while the second line of attack rather depends on experience and the accumulation of data on the behaviour of similar apparatus in service. There are a very large number of textbooks in existence describing the fundamental laws of electrotechnics which only differ in the method of presenting the information. There are also many books available showing how these fundamental principles can be applied in the design of electrical machinery. Textbooks on service experience, however, are almost non-existent, even though this contributes quite as much to the construction of modern apparatus as theory. It is unfortunate that this should be the case, because it is in practical experience that we find the variety, and this phase of our activity certainly justifies far more literature than the other. A fundamental electrotechnical law is permanent and one, or at the most two, well-written books ought to be sufficient in the World. The scope for literature dealing with faults and failures of electrical machinery in service is almost unlimited, since as new industries are electrified, new types of trouble develop.

The translator has been faced with a difficult problem. Not only are there phrases in our own language peculiar to electrical engineers, but equally peculiar are some of the German equivalents for which no dictionary offers a reasonable translation. In spite of this, the English adequately covers the subject-matter, and throughout the book there is close agreement between the German and English editions.

Some of the methods described of rectifying faults are not those normally employed in this country, and in fact, some of the troubles are virtually unknown here. Nevertheless, practical experience in service is always material for debate as to cause and remedy, and the setting out of the evidence on actual troubles in book form represents a distinct step forward in engineering literature.

D. B. HOSEASON

TRAFFORD PARK

SPECIAL NOTE

It is evident that this book cannot profess to deal exhaustively with all aspects of the faults and failures which may be experienced in the operation of electrical plant.

In order, therefore, to extend the scope of future editions, the Author cordially invites readers who have encountered troubles in electrical machines, transformers or apparatus or in the materials used in their construction, to acquaint him with their experiences.

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FAULTS AND FAILURES IN ELECTRICAL PLANT

PART I
ELECTRICAL MACHINES

CHAPTER I
EXCESSIVE TEMPERATURE RISE

1. Definition. In this chapter the excessive temperature rise of an electrical machine is not taken as meaning the overheating of individual parts, such as may occur in disturbances of a localized character, but rather a general rise in temperature throughout the machine. It may happen in a general excess temperature rise of this kind that the safe temperature limits are exceeded at various points in the machine, and that destruction of the surrounding insulation occurs at individual points which are exposed to considerable thermal stress.

In order to save weight and so reduce cost, modern machines are not built to such robust specifications as earlier designs, a point for which every works engineer must allow in comparing earlier and later types when he finds that the earlier type of machine remains cooler. Reliable operation of a machine may be considered as permanently assured as long as the temperature rise of the individual parts remains within the limits laid down in the standard specifications of the various countries.

These specifications are based on many years' experience and research on the thermal strength of the various insulating materials and the performance of the various components—bearings, slip-rings and commutators—at high temperatures. If therefore their temperature rises remain below the values laid down in the specifications, no part of the machine is endangered. Nor will it suffer harm if these values are slightly exceeded for a short time. On the other hand, continual heating above the permissible limit undoubtedly shortens its life.

2. Injurious Temperature Rise. The temperatures which cause damage naturally vary in degree for the individual parts of the machine. A temperature of 150° C. will hardly cause serious damage on a commutator, for example, although the contact surface will probably be changed in colour and the whole commutator slightly distorted. Permanent damage, e.g. of the insulation, need not however be feared. A bearing is capable of running satisfactorily at temperatures of 90° to 100° C. and over, provided the oil employed is suitable.

On the other hand, insulation once overheated loses its electrical and mechanical strength, more or less according to the degree and duration of the over-heating, and the quality of the machine is accordingly lowered.

The maximum temperature to which a portion of a winding and its insulation may be continuously exposed is that temperature at which no injurious change in the insulation occurs due to loosening of the structure. The severest mechanical stress which the insulation must withstand occurs for the most part during manufacture of the winding. A certain reduction in the mechanical strength during service is, therefore, not necessarily serious. It is not easy, however, to estimate the actual extent to which this reduction in mechanical strength is permissible. Results of tests have been published by various investigators* on the change in the mechanical properties of insulating materials, particularly of cotton, silk, paper, and varnished cloth under the sustained action of heat (see Chapter XXXIX, para. 1). Schüler's tests have become the basis of the rules drawn up by the Verband Deutscher Elektrotechniker for the maximum permissible temperature rises.

3. The Maximum Permissible Temperature Rise. The maximum permissible temperature rises for the various parts of a machine are for the most part laid down in the specifications of the various countries† for the testing of electrical machines. In doubtful cases the manufacturer will also supply information.

4. Permissible Overloads. Machines built for continuous operation are often required to withstand short-time overloads. The limits within which this is permissible depend upon the

* Schüler: *E.T.Z.*, 1916, p. 535. Stäger: *Elektrotechnische Isoliermaterialien*, 1931, pp. 139, 160, 276. Möllering: *Elektr. Betr.*, 1924, p. 247. Rayner: *Journal I.E.E.*, Vol. 34, p. 613.

† For example Rules for the Rating and Testing of Electrical Machines, *R.E.M.*, 1930. (In German.) Also see *British Standard Specifications* 168 and 169.

temperature of the machines prior to the overload and upon their design. In the case of large units with windings equipped with resistance thermometers, it is possible to observe the temperature rise satisfactorily during overload and to act before there is any damage. For medium size and small machines measuring instruments of this kind are not usually available and recourse must be had to estimating. A current overload of 125 per cent applied for about 10 to 15 min., 150 per cent for 2 to 3 min., and 200 per cent for 1 to 1½ min. may usually be applied with safety in the case of open type induction motors and d.c. machines up to a rating of about 200 kW. In such cases, the temperature rises allowed by the standard specification may often be exceeded without damage to the machine.

If machines are to run at loads other than those provided for in the tender, it is always advisable to refer to the manufacturer.

5. Temperature Rise Measurements. If it be suspected that the temperature rise of a machine is too high, the first step is to determine as correctly as possible the actual value of the temperature. Estimates of the temperature by feeling with the hand almost always lead to erroneous conclusions. Much practice is necessary to estimate the temperature even roughly by touch. Useful results can be obtained only by using thermometers, thermo-couples, resistance thermometers, and resistance measurements.

(*a*) THERMOMETERS. Since mercury or alcohol thermometers are usually employed for everyday temperature measurements, some remarks as to the importance of inserting them correctly will not be out of place.

Care must be taken in inserting a thermometer at the point where the measurement is to be made, that the value measured is not affected by external influences. In the first place the thermometer must be in proper contact with the part of the machine to be measured and for this purpose the ball of the thermometer should be wrapped with tin-foil. In order to avoid radiation or the effect of currents of cooling air, a small pad of cotton wool or waste about 1 in. in width and length and ½ in. thick should be placed on the bulb and the whole properly fastened with string or tape. Small pieces of wood, or better still, of cork, suitably hollowed out, are also useful for keeping thermometers tightly in place. Fig. 1 shows two examples of the attachment of thermometers. In attaching to

bare parts of windings, care should be taken that no short circuits occur between adjacent turns. For measurements on parts of windings through which heavy currents flow, e.g. coil ends, alcohol thermometers are better, as the mercury bulb may be influenced by leakage fields. Thermometers arranged horizontally or inclined only at a slight angle may give inaccurate readings owing to the "creeping" of the mercury.

If thermometers are to be inserted at points which are only accessible after removal of covers, a considerable time elapses, as a rule, from the shutting down of the machine until the

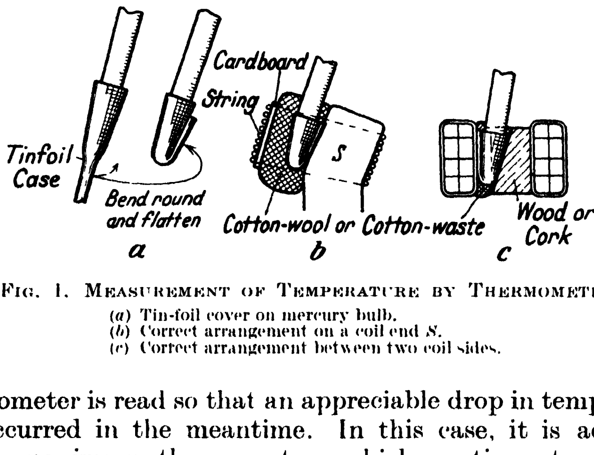


FIG. 1. MEASUREMENT OF TEMPERATURE BY THERMOMETER
(*a*) Tin-foil cover on mercury bulb.
(*b*) Correct arrangement on a coil end *S*.
(*c*) Correct arrangement between two coil sides.

thermometer is read so that an appreciable drop in temperature has occurred in the meantime. In this case, it is advisable to use maximum thermometers which continue to indicate correctly the highest temperature which has occurred during operation or at some time after shutting down, inserting the thermometers in position before starting up the machine.

(*b*) RESISTANCE MEASUREMENT. The resistance of a winding increases with the temperature. If the resistances of the winding in the cold and the warm state are measured, the mean temperature increase may be determined from the variation in resistance in the following manner.

If R_a denotes the resistance measured at the temperature τ_a ° C. with the machine in the cold state and R_e the resistance measured in the warm state with the cooling medium at the temperature τ_e ° C. at the end of the test, the temperature rise of a copper winding during continuous operation may be calculated from the formula—

$$\tau_z = [(R_e - R_a)/R_a] \cdot (235 + \tau_a) - (\tau_e - \tau_a) \text{ °C.}$$

The resistance may either be determined by measuring the current and voltage when direct current is supplied to the winding, or with a suitable resistance measuring box

6. General Causes of Excessive Temperature Rise. If a machine is subject to excessive temperature rises the many possible causes must be investigated

(*a*) ABNORMAL LOADS. On the occasion of an excessive temperature rise the first step is to check the voltage, current speed, and frequency of the machine. If the voltage is excessive, the temperature rise of the iron will increase chiefly owing to the greater iron losses. An increased temperature rise of the winding embedded in the iron is naturally brought about by this increased temperature rise in the iron. In the case of synchronous and asynchronous machines as well as rotary converters, the increased voltage requires a larger exciting current if the speed or frequency remains unchanged, with a consequent increase in the temperature rise of the windings.

Excessive load currents heat up the windings to an abnormal degree and also cause an increase in temperature of the adjacent iron parts. In the case of asynchronous machines an increase in the stator current means a corresponding increase in the rotor current and consequently in the temperature rise of the rotor.

An excessive wattless load, i.e. too low a power factor with normal voltage and kilowatts, necessitates increased excitation of synchronous machines and converters. The chief result is increased temperature rise in the field windings. In the case of converters the temperature rise of the armature also increases.

When machines operate at excessive load currents, permanent damage to the insulation may occur after a short period. The insulating qualities of mica products are, it is true, not greatly impaired since in the first place only the mica carriers—such as cotton, silk, and paper—become brittle or are, at the worst, carbonized. In the case of insulations consisting of cotton, silk, or paper alone, the damage is however, appreciably greater. The layer of insulation which has become brittle will gradually be chafed through, in the case of conductors exposed to any mechanical vibration, and short circuits between turns may occur.

Fig. 2 shows the coil ends of a motor which was overheated for several hours by a continuous overload current. Traces of incipient charring of the insulation are visible on the back of

the end windings, but the insulation on the wires in the centre of the coil is naturally most affected. This overheating and destruction of the insulation ultimately caused a short circuit between turns.

Commutators and slip-rings also exhibit a greater temperature rise on overloads, though not to the same degree as the windings, since in this case in addition to the increased losses due to the current, there also occur appreciable losses due to friction which remain practically unchanged when the current increases.

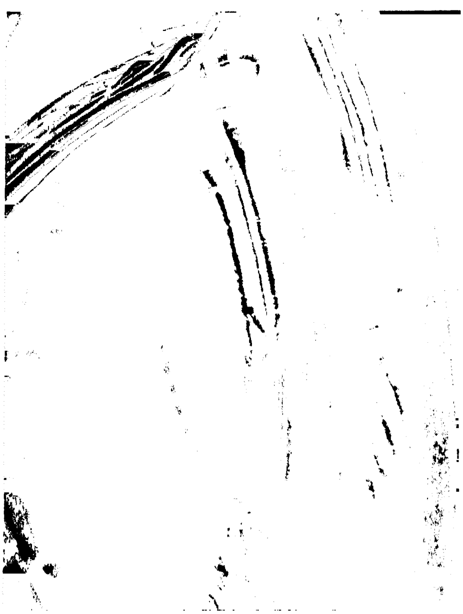


FIG. 2. BURNT-OUT COIL END IN THE STATOR OF A THREE-PHASE MOTOR

Excessively low generator speeds likewise lead to a high temperature rise in the field windings owing to the greater field currents necessary to maintain normal voltage.

(*b*) EXCESSIVE TIME OF APPLICATION OF LOAD. When machines are overloaded for a short time or intermittently, consideration must always be given to the temperature rise. It should be remembered that the temperature rise increases approximately in proportion to the losses. The copper losses increase approximately as the square of the current and the iron losses as the square of the voltage. The B.S.I. Rules for Electrical Machines, Nos. 168 and 169, specify that machines for continuous operation must be capable of—

(I) 50 per cent overload in torque for 1 min.,

(II) 100 per cent overload in torque for 15 sec.,

without injury, after attaining the temperature rise corresponding to rated load.

The temperature rise conditions obtaining in the case of

motors for intermittent operation, e.g. crane drives, etc., are quite special.

In this case the temperature rise is very dependent upon the relative period of connection, i.e. the ratio of the period of connection or load, to the duration of the cycle of operation. Fig. 3 shows, by way of example, how the power varies with a given permissible temperature rise in the case of intermittent operation and with the relative period of connection.

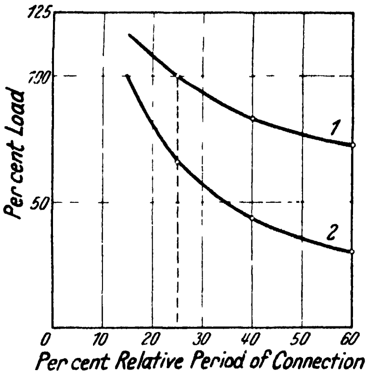


FIG. 3. VARIATION OF THE PERMISSIBLE LOAD FOR DIFFERENT RELATIVE PERIODS OF CONNECTION WHILE MAINTAINING THE TEMPERATURE RISE LIMITS GIVEN IN THE VERBAND DEUTSCHER ELEKTROTECHNIKER RULES FOR ELECTRICAL MACHINES. 200 kW., 500 V., 730 R.P.M. THREE-PHASE CRANE MOTOR

(1) Semi-enclosed design.
(2) Totally-enclosed design.

(*c*) INSUFFICIENT QUANTITY OF COOLING AIR. Other causes of excessive temperature rise are insufficient quantity of cooling air due to the narrowing and stopping up of the cooling air ducts in the machine, restriction of the air flow by improperly built air ducts, or foreign bodies in them, or the accumulation of dust in air filters. In the case of machines with separately driven fans the quantity of cooling air is naturally affected by disturbances to the drives. Fans with curved blades give too little air when the blades rotate in the wrong direction.

The gradual stopping-up of the cooling air ducts of a machine and the covering-over of windings and iron with a heat insulating layer are to be expected, particularly in the case of motors used in the textile, paper, wood, and cement industries. The fine fibres which the air contains everywhere in spinning mills are readily deposited in machines and form coatings of fluff over the ends of the windings, and on the iron, which reduce the air flow and render dissipation of the heat difficult. This fluff will be found to adhere even to very smooth, varnished parts of machines.

Fig. 4 shows the stator of a motor taken from a spinning mill, which, not being equipped with modern machinery, had a tendency to be dusty. This motor was not provided with the protective filters usual in spinning mills, and it was found by

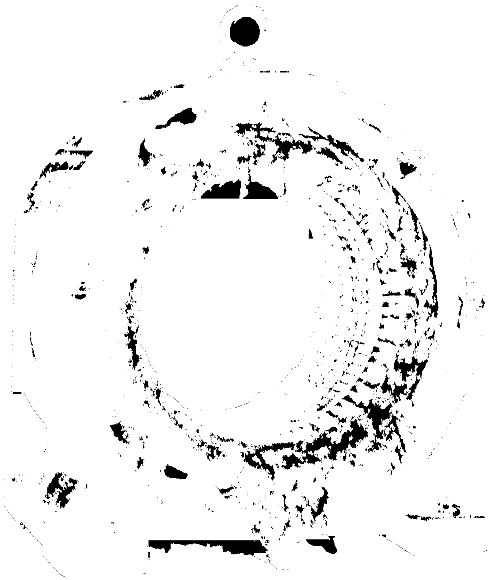


FIG. 4. CONDITION OF THE STATOR OF A THREE-PHASE OPEN TYPE MOTOR AFTER USE IN A COTTON SPINNING MILL

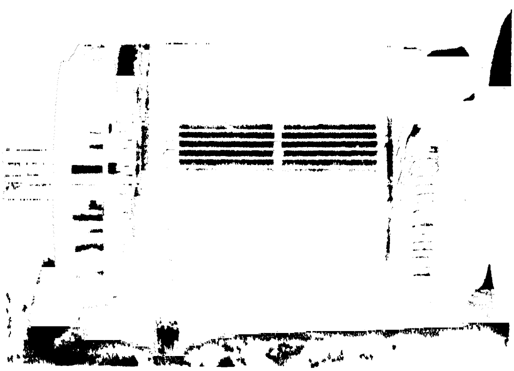


FIG. 5. ROTOR STOPPED UP WITH DEPOSITS OF FLUFF AFTER USE IN A COTTON WEAVING SHED

tests that this deposition of fluff in the open type motor could be reduced to a negligible amount by fitting filters to it. The filters can be cleaned easily when necessary.

Comparative load tests on a spinning motor of this kind in the cleaned and dirty state showed that the temperature rise was with the same load 45 to 65 per cent higher when dirty. The difference was greatest in the temperature rise of the iron and coil ends. The quantity of air passing through the dirty motor was about 60 per cent of that for the clean motor.

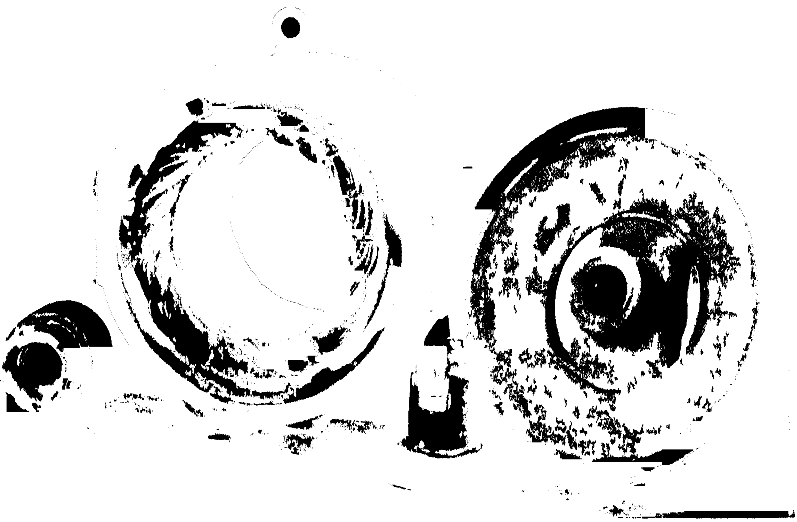


FIG. 6 HEAVILY CLOGGED-UP MOTOR FROM A CEMENT WORKS

Accumulation of size dust in motors working in textile weaving sheds has a very harmful effect. When deposited in the motor, this usually becomes stuck together in lumps. Fig. 5 shows the rotor of a motor of this kind, which was very badly designed in regard to dust accumulation. The solder on the rotor joints had melted out owing to the complete stopping-up of the rotor.

Fig. 6 indicates the severe demands made on motors in cement works. A motor is shown in Fig. 7 which had been in operation for a considerable time in a furniture factory without any attention. The reason for the overheating of these motors is self evident.

Many varied designs have been developed and placed on the market for avoiding the accumulation of dust inside motors. In addition to the totally enclosed motor, whose power in the case of small and medium sizes is between 20 and 45 per cent of that of the same size open type motor, there exist various totally-enclosed fan-cooled designs. In this type of motor the power is also still considerably reduced as compared with the open type and would amount, according

FIG. 7. MOTOR ENTIRELY CLOGGED-UP WITH SAWDUST AFTER USE IN A FURNITURE FACTORY

to the size of the motor, to about 60 or 70 per cent of that of a corresponding open type motor. In addition, it should be noted that the air ducts of totally-enclosed fan-cooled motors—where the external cooling jacket has either cooling tubes or cast cooling ducts—are naturally liable to be stopped up, and the ventilation reduced. Careful maintenance is essential in these cases and the installation of the motors in separate rooms is always advantageous. If this is not possible, open type motors capable of being easily cleaned have much to recommend them.

Where motors are installed in special machine rooms the accumulation of dust is not serious and in these cases six months to a year may elapse between inspections. When installed in

less satisfactory circumstances, cleaning must be carried out without fail at shorter intervals of time.

Choking of the fresh air supply may occur as a result of incorrect lay-out of the foundations in the case of machines with inlets located on the lower side of the casings. In addition, the bad design of air supply ducts, with an excessive number of sharp bends or of excessively narrow cross-section, results in choking of the air. If the points at which air is drawn in from outside are unsuitably located, choking may also occur as the result of the accumulation of leaves and straw, as well as owing to the inadvertent closing of the inlets with boards.

The pressure-volume curve of air flow through a 5 000 kVA. generator is shown in Fig. 8. In obtaining this curve, the cross section of the cooling air outlet was gradually closed. The manner in which the quantity of air drawn by the fans drops continuously as the choking increases and the consequent pressure rise is evident.

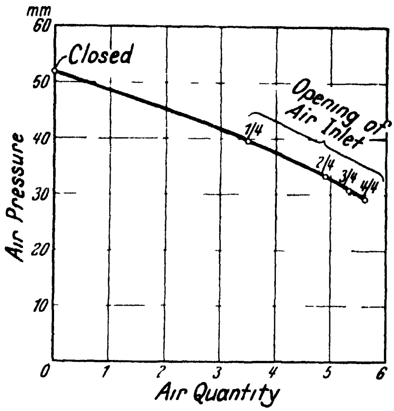


FIG. 8. PRESSURE-VOLUME CURVE FOR THE VENTILATION OF A 5 000 kVA., 750 R P M. THREE-PHASE GENERATOR

It was found that the staff intentionally reduced the air quantity by partially closing the dampers in order to improve the heating of the machine room by the hot waste air. Dampers should not be closed arbitrarily in normal operation but should only be closed when the generator is stationary for an exceptionally long period or in the event of fire. If the machine space is too small, e.g. when machines are installed in narrow passages, excessive temperature rises can likewise occur owing to insufficient supply of cooling air.

Cloth filters were formerly employed for filtering the cooling air, particularly for turbo units. Cotton similar to that used in electric vacuum cleaners was employed as a cloth filter, but the pressure drop in the filters increased rapidly due to stopping-up. In the clean state it should not exceed 0·08 in. water gauge; in the case of a pressure drop of 0·4 in. water gauge, the

filters should be cleaned. Owing to the risk of fire with cloth filters (several cases of fire are known in which the windings of the machines were damaged) increasing use has been made of viscous filters which contain only metal parts and oil of high flash point. In the main, this development made rapid progress during the war when there was a lack of cotton fabric for filters.

The following rules should be noted in the case of air filtering appliances. In any type of plant it should not be possible for any unfiltered air to be drawn in through hidden openings such as cable or other ducts, points of leakage, etc. The pressure drop in cloth filters should be checked at intervals with a water gauge: it should not appreciably exceed 0·4 in. Torn filters should be immediately replaced or repaired. Rooms in which cloth filters are installed should not be entered with a naked light and smoking should be strictly forbidden.

In the case of viscous filters, care should be taken that the cells after immersion in the viscous oil are first properly drained and only reinserted after this, so that no oil is carried into the machine. The velocity of the air through the filter should not exceed 200 ft. per min. The pressure drop should be, if the filters are correctly dimensioned, about 0·4 in. water gauge.

In the case of troubles with cooling systems, if the ventilating air is provided by separately mounted fans, disturbances may arise in the cooling of the main set, unless the drive of these auxiliary fans functions correctly. The normal speed and correct rotation of the driving motor must be checked and the air inlet to the fan examined for possible causes of trouble. In addition, the alarm devices for indicating failure of the cooling air should be checked at intervals to see that they function properly.

(*d*) Ambient Air Temperature is Too High or Air is Insufficiently Recooled. Whenever possible, care should be taken that cooling air is not taken from the same side of the building as is used for exhausting the hot air. Otherwise the danger arises that if the openings are near one another, some of the hot air may be drawn in again. A trial measurement of the cooling air temperature taken directly at the inlet into the machine, and at a greater distance, will quickly give a clue as to whether there is trouble of this kind.

With leaky or partially defective shields between the fresh air and the exhaust air of closed air circuit installations, the fresh air may likewise be preheated and the cooling air only partially circulated.

It may also happen that hot air is sucked through cable ducts, into the low pressure points of a machine, so that the cooling air is again preheated.

If fresh air inlets are located unsuitably relative to the rays of the sun, an excessive temperature rise of the cooling air may likewise occur.

Closed air circuit cooling is usually employed nowadays in order to keep clean the interior of large turbo machines, and also occasionally for low speed generators. In the case of coolers, even when correctly designed, with an insufficient quantity of water the cooling tubes are no longer entirely filled and the cooling becomes partially ineffective, as explained in Chapter XXVIII, para. 3. In addition, calcination and the formation of sludge in cooling tubes will impair the cooling. This process is described in greater detail in Chapter XXXVII, para. 6.

The quantity of cooling water for coolers of this type should be about 3·0-4·0 gal. per min. per kW. loss per 1° C. of temperature rise of the water; with 15° temperature rise, this gives about 0·2-0·27 gal. per min. per kW. If the coolers are liberally dimensioned care must be taken that the elements of the cooler are properly filled and that more water is allowed to flow through if necessary.

With closed air circuit cooling the signalling devices, such as temperature alarms, flow indicators, etc., should have frequent checking. Further, any dampers present for letting in cooling air in the case of a breakdown of the water cooling must be tested for ease of operation. In plants of this kind, arrangements should be made for indicating immediately any pipe fractures occurring in the cooler. In the closed air circuit cooling of very large machines with a separately driven fan it is of the greatest importance that this drive should be absolutely reliable.

(*e*) Incorrect Connections or Broken Leads. In the case of asynchronous motors faulty connection of the stator winding may quite often be the cause of an excess temperature rise in the stator and rotor. In addition, the breaking of a lead to the stator during operation may likewise lead to an excessive temperature rise if the setting of the overload relay is incorrect. Further details regarding this are given in Chapter XII, para. 3.

(*f*) Defective Winding. A high temperature rise may occur

in main pole and inter-pole coils, which are wrapped and impregnated in compound, or varnished, when the filling of the hollow spaces between the conductors is poor. These coils are particularly liable to be damaged if the wrapping gradually becomes loose and air pockets form between the wrapping and the winding, since the intermediate layer of air is a heat insulator. Troubles of this kind are possible with badly wrapped coil ends of stator windings.

A further reason for excessive temperature rise in the coil ends of stator windings, even when the quantity of cooling air is sufficient, is that long coil ends are sometimes insufficiently supported and after a considerable period of service may lie practically on top of one another. As a result the cooling between the winding ends is impaired. In addition, the swelling of the insulation mentioned above in connection with the formation of heat insulating air pockets still further reduces the distance between the coil ends, and the cooling deteriorates even more.

Terminal or distance pieces of insulating material arranged for holding up the winding parts may cause local overheating, if they overlap appreciably the cooling surfaces and so render them ineffective.

If in synchronous or d.c. machines a portion of the field winding becomes ineffective due to a short circuit in the turns or layers, the exciting current must be increased in order to maintain the correct voltage. As a result there arises the risk of overheating in the portion of the field winding which still remains effective.

(*g*) OTHER CAUSES OF EXCESS TEMPERATURE RISE. There are, of course, other troubles in windings and core which can cause overheating. The trouble in such cases, however, always makes itself felt at defective points and in their immediate vicinity. This question is dealt with in greater detail in Chapter II.

Slip-rings and commutators become too hot if the cooling is inadequate as well as when a wrong type of brush is used. Further details will be given of these troubles and of their elimination in Chapters IV and V. Excessive temperature rise in the bearings may be due to various causes; these are specially dealt with in Chapter VII.

Errors in design may, of course, also be responsible for excessive temperature rises in the individual parts of machines.

This matter will not be dealt with further here, since the leading electrical manufacturing firms nowadays have sufficient experience and testing facilities so that such defects cannot fail to be observed at the works.

CHAPTER II

TROUBLES IN WINDINGS

1. Damp Windings. (*a*) Causes of Penetration of Moisture. When machines are stored for lengthy periods in damp, poorly ventilated rooms, or are shut down for a considerable time, particularly during the damp seasons of the year, or become wet during transport, or are exposed to steam, the insulation is capable of absorbing so much moisture that starting up without drying out may involve damage to the windings. Store-rooms for completed machines should therefore always be well ventilated and, if possible, moderately heated during damp spells. In addition, spare windings should for the same reason be stored in dry and well ventilated rooms and not be left in the packing case. The windings of machines whose cooling air is taken from the open and which are shut down for lengthy periods, frequently for weeks and months, can become very damp during humid foggy weather by the penetration of air. It is usually possible to close the inlet and outlet ducts of such machines and this measure is always to be recommended during long periods of shut-down and in damp weather. When the air is dry and the weather warm, the cooling air ducts should, on the other hand, be opened. Machines installed out of doors are also likely to have condensation water inside them as the result of considerable variations in the temperature. The same danger also exists after the transport of machines when they are suddenly brought into rooms with a warm, moist atmosphere after having been for some time in cold air.

(*b*) Measurement of the Insulation Resistance. In order to obtain an idea of the state of dryness of a winding the insulation resistance to earth should be measured. In the case of multiphase windings, the insulation resistance between the individual phases, provided the latter can be separated electrically, should also be measured.

The insulation resistance can only be correctly measured with direct current, since if alternating current is employed the charging currents occurring affect the measurement, because the winding and frame separated by the insulation as a

dielectric, form a condenser. It is advisable to use one of the well-known insulation testers, in which the test voltage, which should be as constant as possible a d.c. voltage, is produced in a small, hand-operated, built-in generator.

In the case of inefficient apparatus producing only a very irregular d.c. voltage the peak voltage may, according to Keinath, be four times as high as the average d.c. voltage.* As a result, measurements are inaccurate and the insulation is stressed to an unnecessary degree, particularly in low-tension machines. The magnitude of the test voltage depends on the instrument; insulation testers are built for voltages of 250 to 1 000 volts and over. As a rule, an apparatus with a test voltage of 250 to 500 volts is adequate, particularly where it is also to be used for testing low-tension machines.

In measuring the insulation resistance, the machine must be isolated from other parts of the plant and the reading should only be taken when the deflection of the instrument has become constant. The windings of large machines possess a considerable capacitance; a certain time, therefore, elapses before the deflections reach their final value. The resistance measured may vary according to the value of the test voltage; the same test voltage must therefore always be employed in order to obtain comparative values.

In the case of machines whose windings possess a large capacitance, the hand-operated tester is no longer suitable for insulation measurement and one of the standard resistance methods of measurement must be employed. These require a d.c. supply source with as constant a voltage as possible. The necessary instruments for these measurements are usually not available in the average maintenance department.

(*c*) Minimum Allowable Insulation Resistance. The value of the insulation resistance depends upon the dryness, the temperature, the insulating material employed, and its thickness, as well as on the area covered by the insulation. The material and its thickness are governed by the working voltage, the area covered with the insulation depends upon the rating of the machine and the number of poles.

No general rule can be given for the minimum insulation resistance permissible for a winding. An attempt will, however, be made to give an idea of the order of magnitude by taking a few practical values.

* Keinath *Die Technik elektrischer Messgeräte*, Vol. 2, p. 233.

For a.c. generators with rated voltages of 3 000 volts and over, between 2 and 20 poles and outputs of 30 000 kVA. the insulation resistance of the stator winding in a properly dry condition should attain in service a value of approximately 1 MΩ. per 1 000 volts working voltage. With a larger number of poles such values would only be attained after a lengthy period of continuous operation, i.e. with the winding in an absolutely dry state. Insulation resistances of 0·2 to 0·5 MΩ. per 1 000 volts are, however, sufficient, and do not endanger the operation of the machine. In the case of low-tension machines values of 1 to 2 MΩ. are satisfactory.

As a rule insulation resistance values of at least 0·1 to 0·5 MΩ. are adequate for the rotating field windings of low speed a.c. generators: insulation resistances of 1 MΩ. and considerably over are frequently measured on turbo rotors.

The stator windings of asynchronous motors attain the same insulation resistance values as those of synchronous generators. Insulation resistances of 0·5 to 3 MΩ. and upwards are possible in the rotor windings of asynchronous motors according to the rated output and the rotor voltage.

D.c. machines of high outputs and voltages up to 1 000 volts may have armature windings with insulation values of 2 to 10 MΩ. and over; the insulation resistance of the field windings lies within approximately the same limits.

It may once more be emphasized that the measured insulation resistance depends very largely on the temperature and voltage and on the type of instrument employed. In addition, it must be remembered, in analysing the test results, that the insulation resistance may be reduced on a dirty winding, for example, by carbon dust in the case of d.c. machines.

The following formula for the stators of synchronous machines taken from the *A.I.E.E. Standards** also gives some idea of the magnitude of the insulation resistance at a temperature of about 75° C.

$$\text{Insulation resistance} = V/(N + 1\,000)\ \text{M}\Omega.$$

in which V denotes the rated voltage and N the rated apparent output in kVA. It is required in these standards that the rotor winding of turbo generators of 500 to 25 000 kVA. should possess an insulation resistance not less than 1 MΩ. at 75° C.

The formula given does not take sufficiently into account

* *A.I.E.E. Standards* No. 7, December, 1927.

the dimensions of the machine, which govern the insulated area and in consequence the insulation resistance. It should also be observed that the insulation resistance to earth calculated from this formula holds good for the entire windings; all three phases of three-phase windings should accordingly be joined together for testing.

The insulation resistance of a winding is considerably greater when cold than in the warm state; it is therefore advisable to determine the resistance as far as possible in the warm condition. If the insulation resistance of the machine when cold only attains the minimum value given by the above formula, the machine should be dried out or it should have a reduced voltage applied for some hours before applying the rated voltage.

2. Drying-out of Damp Windings. As a rule small low-tension generators and motors can be placed in commission without previously drying, an exception being made for machines which have become wet during transport or storage. If it is found in measuring the insulation resistance that the insulation of the windings is damp, careful drying should be carried out by heating.

In the case of large high-tension units, on the other hand, a short period of drying should always be carried out before the machine is put into service. For this purpose, generators can be run for 12 to 24 hours without voltage in order to dry them out by the action of ventilation; motors should if possible, be put into service at reduced voltage. The drying method to be employed for damp windings depends on the type of machine and the expedients available on site. The chief thing in drying is in all cases to pass plenty of air through every part of the windings.

A.c. generators which can be brought up to speed by their driving machines obtain sufficient ventilation through their own fans. The generator can be warmed either externally by artificially heated air, or internally by the heat due to losses in the iron or copper.

The introduction of dry and clean heated air is of special importance in thoroughly saturated machines. It is not advisable to bring them up to voltage, however small, or to run them short-circuited. Heating resistances can be built into the air supply duct for heating the drying air and supplied by an auxiliary source of current, e.g. the actual exciter. The drying

air should have a temperature of 50 to 70° C. and it is advisable to heat up to this temperature slowly over a period of 2 to 5 hours. With normal speed the quantity of air conveyed is so great that quite considerable heating capacities would be necessary for the purpose. The speed of the generator should accordingly be reduced as much as possible and the supply of fresh air throttled down so that it moves at a reasonable speed. If it is possible by closing the air dampers to reverse the ventilation so that the air expelled is again drawn in, and the cooling air can therefore flow in a cycle, a still smaller heating capacity is sufficient for warming the air. It is, however, essential to supply a quantity of dry, fresh air and to exhaust part of the warm, moist air, or completely renew the entire quantity of air from time to time.

The hot exhaust air of adjacent machines may also be passed through the damp machine for drying it.

If the windings have only become damp due to storage, or if it is a question of a generator being put into service for the first time, the following procedure may be adopted in drying out. The machine is brought up to full speed and first run without voltage with the full supply of fresh air. In foggy or rainy weather the fresh air should be taken from the machine house, or better still, the warm air of other machines should be used. Running in the unexcited state can be carried out for 2–10 hr. according to the rated voltage and the state of dryness of the winding. After this, the machine is slowly excited without any load. If the star point connection is accessible, it should be isolated; any earth connection of the star point should likewise be removed. The time in which the rated voltage may be reached is governed by the working voltage of the machine. If the windings are not very damp, i.e. the insulation resistance is higher than that given in the formula in Chapter II, para. 1 (*c*), the voltage should be slowly and continuously raised to the rated value within the following times—

Rated voltage of the machine (V.)	Time (hr.)
500	2
2 000	3
5 000	4
10 000	5
Over 10 000	6

In the case of low insulation resistance values, the generator should be run for some time at 30 to 60 per cent of the rated voltage, at reduced speed and with the air supply throttled for the purpose of warming it up gradually. The speed should only be reduced to such an extent that the rotating field current is at first not higher than one-third to one-half of the rated value. The heating of the rotating field winding should be observed by noting the increase in the resistance. An appreciable rise in temperature is possible in 3 to 6 hours by throttling down the fresh air, or by circulating the cooling air. The temperature in the stator should be checked by thermometers placed on the core. This temperature should not exceed 50 to 60° C. and once it is reached the supply of fresh air should be regulated to keep it approximately constant. Drying of the generator is then continued until a sufficient improvement in the insulation resistance is reached. For purposes of measurement the machine should be shut down at intervals of 2 to 5 hours. As the dryness and insulation resistance increase the voltage and speed of the machine should be raised, the supply of fresh air being simultaneously increased, but no appreciable cooling must take place. On completion of drying, the generator is then cooled down for 2 to 5 hours by giving the full supply of air, the voltage increased some 10 to 20 per cent above the rated voltage for about half an hour, and finally the machine put into service. In normal operation a further gradual increase in the insulation resistance will take place.

The copper losses are often used for heating the machine instead of the iron losses as described above. For this purpose the machine is short-circuited by connecting the leads together through a current transformer for measuring the stator current. The machine is then brought up to the rated speed and at first only excited to such a degree that about 40 to 50 per cent of the rated current flows in the stator winding. It is not advisable in this case to throttle the fresh air supply. Regular measurement of the temperature in the winding during drying is important, since an excessive temperature may damage the insulation. The stator current is raised in the course of several hours as the dryness increases, until sufficient insulation resistance is obtained. This process can, however, lead to damage to the windings, particularly in the case of machines of very great core length, owing to the uneven temperature rise in winding and core. Moreover, in very damp windings which

are not dried carefully, bubbles may form in the insulation, particularly if the current is raised too quickly.

The insulation resistance at first drops continuously during drying and reaches a minimum value, again increasing as drying is continued. The variation in resistance during drying observed when placing a large three-phase generator in commission is shown in Fig. 9.

D.c. generators can be dried on short circuit provided their

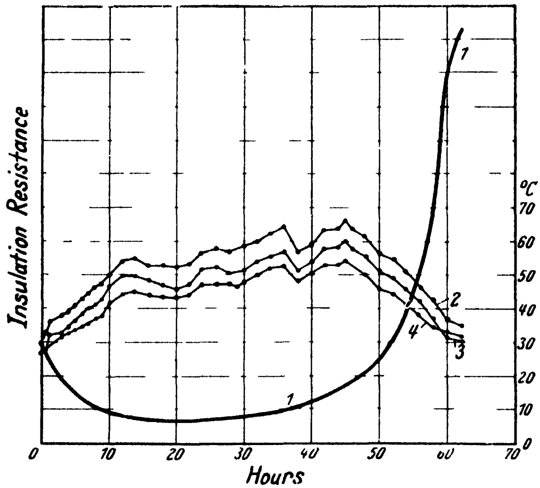


FIG. 9. VARIATION OF THE INSULATION RESISTANCE DURING DRYING OF A THREE-PHASE GENERATOR

(1) Insulation resistance
(2) Temperature of winding measured with resistance element
(3) Temperature of core measured with thermometer
(4) Temperature of drying air

windings are not very damp. For this purpose the machine must be separately excited with quite a small field current; the brushes in this case must be shifted about one segment in order to avoid self-excitation. As a rule, however, running on no load for several hours without excitation is quite sufficient to give adequate insulation resistance. If the windings are very damp, complete drying-out on short circuit is not to be recommended owing to electrolytic action, and it is then necessary to dry with warm air as described above.

Motors are dried either by means of an external drive and ventilation for a sufficient length of time, or by passing warm air into them. If this is not feasible, they can at first be run

on no load at reduced voltage, e.g. in the case of asynchronous motors at one-fourth to one-fifth the rated voltage. Large d.c. motors for winding plant, rolling mills, etc., can be dried at standstill by supplying the non-excited motor from the Ward-Leonard generator with current of 40 to 60 per cent of the rated value. The temperature rise in the windings in this instance should be checked by thermometer. It should also be noted that an unloaded motor of this kind with a small brush displacement from the neutral zone may start up and run away.

The stator and rotor windings of synchronous and asynchronous machines can also be heated and dried by supplying them with direct current, provided the machines are dismantled. In view of the electrolytic action, this method should, however, only be employed if the windings are not very damp, as already mentioned In order to attain a sufficiently high temperature, the parts of the machine to be dried should be covered with fabric or boards and openings for the passage of warm air should be left in these coverings. Preheated air can at the same time be blown in so as to increase the effect. It is best to carry out drying with warm air if the necessary equipment is available. In drying multiphase windings with direct current, the connections of the direct current leads must be interchanged from time to time so that all phases of the winding are dried as uniformly as possible. In employing direct current the temperature rise in the winding can also be ascertained very simply from the increase in the resistance as described in Chapter I, para. 5 (*b*).

The drying of the rotor of a 2 200 kW. three-phase motor by supplying it with direct current can be taken as an example. The connections were changed in each case after 1 to 2 hours. To enable a temperature of about 60° C. to be reached, the winding of the rotor was totally enclosed with boards, the necessary heating capacity amounting to 8–10 kW. or about 0·3 to 0·5 per cent of the motor's rating. The steady temperature was reached after about 6 hours. Continuous measurement of the insulation resistance yielded the values given in the table on p. 24.

If windings have been exposed to the effect of sea water, they must be thoroughly rinsed with fresh water before drying, in order to remove any salt.

In drying machines it is a mistake to imagine that there is

Time (hr.)	Insulation resistance (MΩ.)
0 (on commencement)	0·2
After 12	0·03
,, 24	0·1
,, 36	0·8
,, 50	5·0

any inherent value in mere quantity either of heat or air, and to employ a high temperature with the erroneous idea of drying as forcibly and speedily as possible. It is of much greater importance for the reliability of a machine to dry it slowly and carefully while taking note of all the phenomena which occur. Undue haste to save a few hours in the drying time may lead to considerable damage to the insulation for which the gain in time does not compensate. Even a machine which has been thoroughly saturated by the direct action of water can be put into proper working order by correct drying.

Machine manufacturers are always prepared to give advice on methods of drying.

The active iron may, of course, also be affected by rust forming under the action of moisture. If accessible, the stampings should be carefully cleaned by scraping off the rust, and coated afterwards with a good insulating varnish, preferably with the iron in the warm state. It is possible to prevent further rusting between the teeth by properly drying the heated stampings and treating them with varnish, even when the rust has penetrated, provided the machine remains continuously in service and does not become damp again.

The insulation qualities of an old machine are frequently checked by means of a high voltage test after reconditioning by drying. It should, however, be noted that every high voltage test is a severe strain on the insulation which is unnecessarily weakened by frequent repetition of the test. The appropriate specifications of the various countries give instructions in regard to the performance of such tests* and to describe them would be beyond the scope of this book.

It is advisable to test old machines with lower voltages than those employed for new machines, say two-thirds to three-quarters or so of the test voltage for new equipment.

* Cf. for example, Verband Deutscher Elektrotechniker *Rules for the Rating and Testing of Electrical Machines*, 1930.

3. Breakdowns to the Iron. (*a*) CAUSES OF BREAKDOWNS. A variety of insulation troubles may lead to breakdowns between winding and core. Excess voltage in the lines to which the machines are connected, as well as excess voltages in the field windings due to disconnection, may bring about puncturing of the insulation or flash-overs along the surface of portions of the insulation, and in consequence breakdowns to the core. In addition, earths may occur at normal voltages if leakage paths are formed over the insulation due to dust or flash overs, and puncturing is assisted by moisture. Bridges formed by dust frequently produce earths in the armature windings and commutators of commutator machines, as well as in the rotor slip-rings of synchronous and asynchronous machines. These disturbances are usually connected with pronounced brush wear when an unsuitable choice of brush has been made, or with electrical or mechanical defects in the brush-gear. In addition, considerable dust may accumulate when the current collecting parts are not maintained in good condition. Drives in the iron and coal industries, rolling mills, winding plant, coking plants, etc., are particularly liable to this. When the cooling air is taken from the shops, dust penetrates the rotor windings, commutators, and slip-rings and forms conducting bridges which may gradually lead to earths. The dust contained in the air is light, and so finely distributed that it is carried by the cooling air far into the interior of the machines.

The commutator necks should be carefully covered with paper or cloth when turning or polishing commutators. Powdered copper or filings may produce earths in addition to short circuits between turns. Air may contain, in chemical works for example, gases and vapours as well as dust, whose condensation on the insulation may lead to flash-overs and also earths. Machines which have stood for lengthy periods in such surroundings are particularly affected in this way.

Defects in the insulation have also been observed after careless use of soldering flux in repairing coils. If the soldered joints are not made carefully, the adjacent insulation may be burnt so that earths are possible, and burnt insulation should always be replaced. If bakelite insulations are superficially charred, the damaged places must be very carefully cleaned by scraping and revarnishing.

In addition, mention must be made of mechanical causes of breakdowns to earth. Extraneous matter may enter machines

with the cooling air due to the inattention of the staff, or to an insufficiently protected air inlet. This affects the insulation mechanically and produces conducting bridges between live parts and earth.

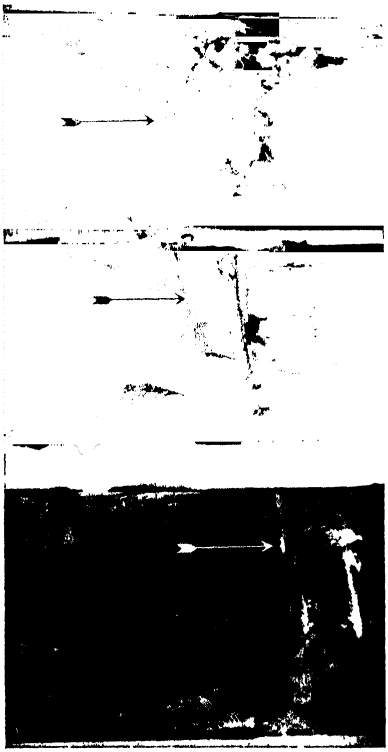


FIG. 10. DAMAGE TO THE COIL INSULATION OF A 3 500 kVA. SINGLE-PHASE GENERATOR CAUSED BY LOOSE END PLATES AND LOOSE PRESSURE FINGERS

Parts which have become loose due to the gradual weakening of riveted or welded joints on distance pieces in the cooling vents, or on the pressure fingers of end plates, suffer from continuous vibration and may damage the adjacent coil insulation. If individual points in the laminations are not under sufficient pressure, the teeth may begin to vibrate and the insulation of the embedded windings may be gradually worn through by friction. Fig. 10 shows the effect of loose end plates and loose pressure fingers on the adjacent coil insulation in an old 3 500 kVA. single-phase generator. Fig. 11 shows a breakdown to earth in the stator of a single-phase turbo-generator of 1912 design; this was due to insufficient pressure on the laminations, so that vibration occurred in the teeth. With the methods applied nowadays in assembling stampings and pressure fingers, and with the robust design of stampings, such defects are unlikely to occur on modern machines.

Amongst the foreign bodies of many kinds found in machines are dust and sand of every description, cotton waste, tin-foil, pieces of wire, screws, tin, etc. Fig. 12 shows an interesting effect produced by extraneous matter. Small pieces of iron must have fallen in when inserting the slot wedge and become

wedged in between the bar insulation and the wooden wedge These small pieces of iron were continuously moved to and fro by magnetic forces, and in the course of about four years formed the notches in the coil insulation and wedge visible in the picture. Had not these places been accidentally discovered

FIG. 11 BREAKDOWN TO EARTH DUE TO LOOSE LAMINATIONS IN THE STATOR OF A 1912 FOUR-POLE SINGLE PHASE TURBO GENERATOR

during repair, both earths and short circuits between turns would have occurred with serious results.

The insulation of windings may be appreciably modified by overheating due to overload or ageing following very lengthy periods of operation. If carbonization occurs, the insulation may puncture even during normal operation, or on the occurrence of small excess voltages. Puncturing may

occur under the influence of mechanical or electro-dynamic forces. In this connection, there is the rubbing through of the insulation supports of rotating field coils due to centrifugal forces, the shifting of field coils in the case of reversible drives (winding and rolling mill motors), and the loosening of portions of the stator or rotor windings by frequent current surges in the case of motors which are repeatedly started up. Short cir-

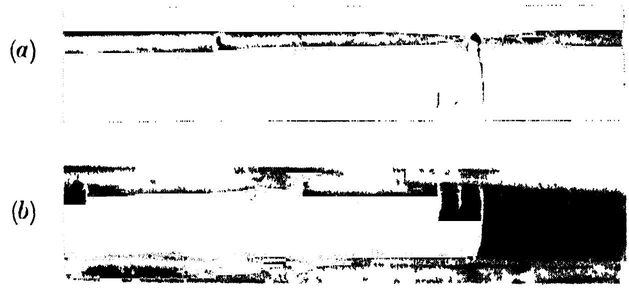


FIG. 12. DAMAGE TO THE COIL INSULATION AND SLOT WEDGE BY AN IRON TURNING.
(a) Coil (b) Wooden wedge

cuits between turns, which burn the insulation, may also cause breakdowns to earth.

(b) CONSEQUENCES OF BREAKDOWNS TO THE CORE. In all machines with frames not insulated from earth, i.e. in practically all cases, breakdowns to core also always mean a breakdown to earth. If properly earthed the casing will, as a rule, not assume a dangerous voltage to earth. Contact with machines having insulated mountings may, however, be risky if faults to the core occur.

The earth may be either continuous or intermittent. In the case of a continuous earth the point affected is usually burnt through, as a steady arc is formed. Lengthy duration of the arc from lack of suitable protective devices is particularly harmful. A short circuit between turns, and under certain circumstances a breakdown to the core at two places and consequently a short circuit in the winding, can easily arise from a simple fault to core. The core as well as the adjacent parts of the winding may suffer considerably from the arc.

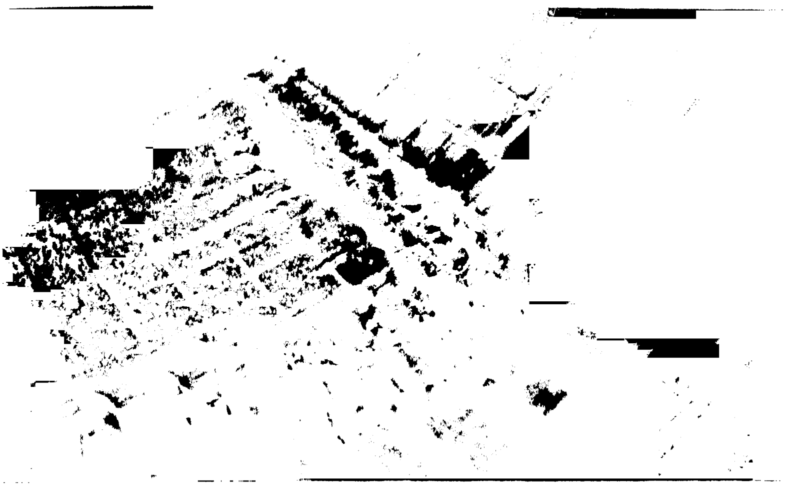


FIG. 13. EFFECTS OF BREAKDOWN TO EARTH IN THE STATOR OF A 4 500 kVA. ALTERNATOR

Fig. 13 shows an example of the effects of faults to the core and the resultant short circuit between turns on a 4 500 kVA. alternator. The core was scorched over a large surface and it was necessary to insert new stampings in the machine. Fig. 14 shows cavities burned in the armature of a 900 kW. d.c. generator. The extension of the trouble to the adjacent slot was chiefly caused by the fact that the machine attendant, having disconnected the machine on observing smoke during normal operation, connected it up later without further investigation. A short circuit between turns followed the fault to core.

FIG. 14. BURNING DUE TO A BREAKDOWN TO EARTH IN THE ARMATURE OF A 900 kW. D.C. GENERATOR

Fig. 15 shows the effects of a stroke of lightning in the coil of a 750 kVA. 10 kV. three-phase generator.

4. Locating a Fault to Core. If the point at which the fault to the core has occurred is not burnt to such a degree that its

location is at once clear, it must be found by measurement and test. In the first place the group of windings affected is separated out by eliminating the sections of adjacent winding. Various methods of investigation are employed for finding the exact position of the fault. We will only mention those which can be carried out with the test instruments usually

FIG. 15 COIL OF A 750 kVA 10 000 V THREE-PHASE GENERATOR DAMAGED DUE TO THE EFFECT OF LIGHTNING ON THE SUPPLY

available in works. Other apparatus for determining the point of defect are available in repair shops as, for example, bridges for resistance measurements, and listening devices with telephones.

(*a*) RESISTANCE MEASUREMENT METHOD. The winding is supplied with d.c. or a.c. from an auxiliary ungrounded source of suitable voltage as depicted in Fig. 16. Measurement with a.c. should only be carried out on rotating fields and stator windings with the rotor removed. Otherwise dangerous voltages may be induced under certain circumstances in the stator or rotor. The partial voltages v_1 and v_2 to core are measured with an applied supply voltage v_3. If the resistance of the instrument is sufficiently high or the contact with the iron is direct, the contact resistance at the fault is negligible, so that $v_1 + v_2$ becomes equal to v_3. Conclusions can then be drawn as to the position of the fault from the ratio of the partial voltages. These measurements can also be carried out on rotating field windings with the machine running and the exciter used as a source of current.

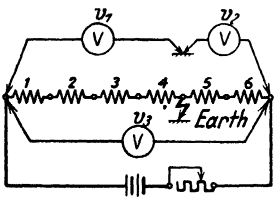


FIG. 16
LOCATING A BREAKDOWN TO THE IRON BY MEASURING THE PARTIAL VOLTAGES v_1 AND v_2

(*b*) DIRECTION OF CURRENT METHOD. The above method is not suitable for the windings of machines of low voltage and

heavy current. The partial voltages are so small owing to the low resistance that they cannot be measured accurately with the instruments usually available. Nor can this method be employed for the armature windings of d.c. machines unless they are opened.

In such cases the following method should be employed. The section of winding, e.g. of an a.c. stator as shown in Fig. 17, is supplied by connecting both ends of the winding to one pole of a d.c. source and the core to the other pole. A distribution of the current then occurs in the winding in the direction of the fault corresponding to the direction indicated by the arrow. If the current is large, the point at which the direction of the current changes can be found with a magnetic compass by moving it over the slot and conductor The direction of the current can also be found in a different way with a sufficiently sensitive instrument (e.g. milli-voltmeter). The direction of the current can be clearly recognized by observing the voltages at the coil connections. This method of investigation is, however, only applicable to windings in which the end connections are bare. Fig. 18 shows diagrammatically the method of testing a section of a three-phase winding. If the voltages between *a-a*, *b-b* and *c-c* are measured with the fault to core still existing, the voltmeter connections must be changed at *c-c*, in order to obtain a positive deflection. The direction of the current in this end connection is then opposite to that in the two other connections.

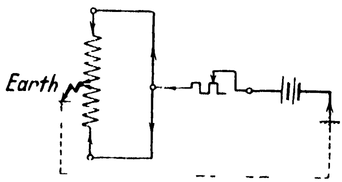


FIG. 17.

CURRENT DISTRIBUTION IN A WINDING WITH AN EARTH WHEN SUPPLYING CURRENT THROUGH THE WINDING AND THE CORE

In three-phase windings the phase in which the fault is present is frequently not known beforehand. It is advisable in such a case to connect the terminals together and with the star-point, if there is one, and to connect the supply, as indicated in Fig. 17, to the sections of winding so connected and to the core. The sound phases now carry no current. If the compass is passed over the slots belonging to these phases, no deflection of the needle will be observed.

A fault in the armature winding of a d.c. machine can be also detected with the compass in the following manner. If

the supply is connected between the commutator and the core and all the bars short-circuited by a bare metal strip or a sufficiently thick piece of wire, a marked deflection of the compass needle will be observed at the points of breakdown.

(*c*) BURN-OUT METHOD. If a direct breakdown to the core has been discovered by measurements with a megger or a test lamp, the position of the fault can be revealed by the burn-out method. For this purpose an external very low d.c.

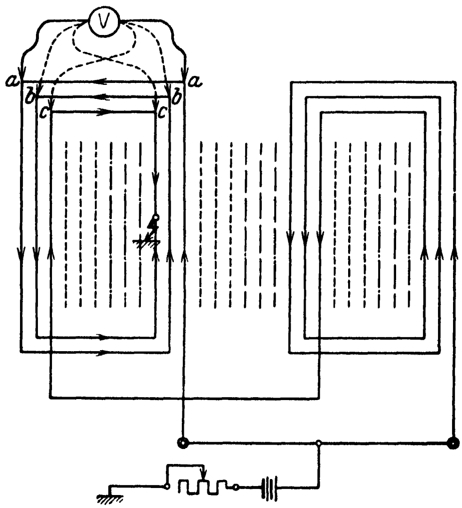


FIG. 18. DETERMINATION OF THE CURRENT DISTRIBUTION BY MEASURING THE VOLTAGE DROP IN THE COIL ENDS OF A STATOR WINDING

or a.c. voltage, often only of a few volts, is applied between the core and the winding. The current flowing through the fault heats the latter; smoke and not infrequently sparking may be observed at the fault. In order not to increase the damage due to scorching of the surrounding core, it is necessary that the applied voltage be small and that where possible an excessively high current is avoided by sufficiently large series resistances.

(*d*) REPAIR OF BREAKDOWNS TO THE CORE. The procedure to be adopted in eradicating the fault depends on the cause and the consequences. If dust bridges are the cause, the points of leakage should be carefully cleaned, burnt insulation being

scraped away and re-varnished. Repetition of the trouble can be prevented by periodical cleaning of the affected parts. If considerable dust has accumulated due to brush wear, more suitable types of brush should be chosen, and the commutation or collection of current at the slip-rings improved. Careful turning of the commutators or slip-rings alone is frequently sufficient.

If portions of the winding have to be re-insulated, new coils should be ordered from the manufacturers, particularly in the case of high-tension machines. Low tension windings can often be reconditioned in the works repair shops. The method of insulation of such windings should be as nearly as possible that employed by the manufacturer.

Burnt cores can usually be restored by filing and chiselling the affected parts. The smooth running of a machine will not, as a rule, be affected by such treatment even if rather large portions of a tooth have to be chiselled away. The only matter of importance is to see that the individual punchings are carefully separated from one another and again insulated by inserting paper or pressboard, or by a coating of insulating varnish, so that fresh troubles in the core do not occur due to local overheating. If the core is badly damaged, the stampings should be removed and new stampings inserted. This should be done by the manufacturer of the machine.

5. Short Circuits between Turns. (*a*) CAUSES OF SHORT CIRCUITS BETWEEN TURNS. Like faults to core, short circuits between turns and layers are traceable to various causes, such as excess voltages originating in the other parts of the plant, weaknesses in the insulation of adjacent conductors due to overheating, ageing, the accumulation of dust, and the effects of mechanical or electro-magnetic forces. Solder which escapes from the soldered joints of coil ends during overheating and penetrates between the conductors may also lead to short circuits between turns. Flash-overs between the coil ends of the rotors of asynchronous motors and commutator machines are possible when bridges of conducting metal dust and carbon dust form, although they may not always lead to continuous short circuits between turns.

(*b*) CONSEQUENCES OF SHORT CIRCUITS BETWEEN TURNS. If one or more turns of a generator winding are short-circuited by a fault, a heavy current flows. This may quickly overheat the parts of the winding in question and smoke appears. If,

the trouble is not immediately attended to, other adjacent parts of the winding and the core may be affected and the winding may even catch fire. Fig. 19 shows the effect of a short circuit between turns of a stator coil of a 700 kW. three-phase motor. The coil insulation is entirely burnt, the adjacent coils being much charred and even the core affected.

Humming and vibration may be observed on the occurrence of short circuits between the stator turns of a.c. machines.

FIG. 19. SHORT CIRCUIT BETWEEN TURNS IN THE STATOR OF A 700 kW. THREE-PHASE MOTOR

A.c. motors affected with short circuits between turns of the stator usually fail to start up. When the switch is closed, it will frequently be tripped again by the overload protection. In the case of permanent short circuits between the rotor turns of excited commutator machines, considerable sparking in addition to smoke is usually observed even on no-load, and the segments corresponding to the affected coil rapidly become blackened. If the armature winding is fitted with equalizing connectors, other segments twice the pole pitch distant will also be blackened. For example, three groups of segments displaced 120° with respect to one another have been observed to be burnt on the commutator of a 6-pole machine. A short

circuit between turns of the armature of a rotary converter burnt not only the bars belonging to the affected coil, but those of all the other coils connected directly to the same slip-ring. Occasionally the short circuit between turns is not initially a permanent one, but is produced by accumulation of dust on the coil ends or bars. The coil in question is not at once greatly overheated but there is intensified sparking, and burning of the bars. Only after a lengthy period of operation can a more

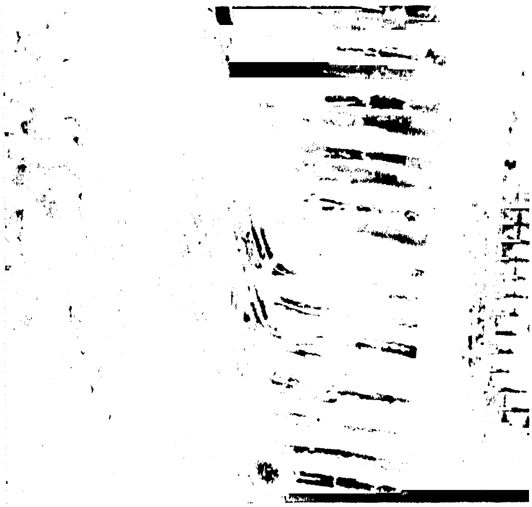


Fig. 20. Short Circuit between Turns Due to the Accumulation of Carbon Dust between the Coil Ends of a D.C. Armature

intense local temperature rise in the affected coil be observed by feeling the winding which finally overheats. Fig. 20 shows the effect of a short circuit between turns caused by the accumulation of carbon dust in the armature of a d.c. machine. Dust bridges can be clearly seen between the conductors.

In the case of field windings a short circuit between turns rarely causes appreciable burning. Only traces of scorching are apparent at the point of contact. If only a few turns are bridged by the short circuit, the fault scarcely makes itself perceptible in the running of the machine. Only when a whole section of the winding of a pole coil has become ineffective due to the short circuit between the turns can an intensified sparking at the brushes occur as a result of the lack of magnetic

symmetry in d.c. machines with series-parallel and multiple circuit armatures. With synchronous generators and motors vibration occurs when the excitation is increased. In the case of asynchronously started synchronous motors, short circuits between turns of the rotor may impair starting, a greater temperature rise in the affected parts of a pole being perceptible.

6. Locating Short Circuits between Turns. Some simple methods are given below for locating short circuits. Methods of investigation requiring special instruments only available, as a rule, in repair shops and factories are not included. This applies especially to the test magnet method employing a telephone receiver.

(*a*) External Examination of the Winding. Unsound coils in windings, if they have been intensely overheated, are, as a rule, quickly identified by the charred insulation on the coil end or by the abnormal temperature rise. Frequently the damage is so extensive that it can be recognized at the first glance. If considerable burning has not occurred, due to the functioning of protective apparatus, or attention has been drawn to the danger by the smoke and the machine has been shut down, an unsound coil usually appears hotter than a sound one on feeling the winding. A keen sense of smell is also a help to the investigator in such cases.

If the fault cannot be discovered, the machine should again be run very carefully for a short time; generators in such cases should be excited very gradually to a small voltage and observed for smoke or vibration. The winding should be repeatedly felt immediately after the machine has been quickly brought to a standstill. Motors should be connected for a short time to the supply, if possible with reduced voltage, and observed in the same way. The procedure is similar in the case of d.c. machines if a short circuit between armature turns is suspected.

(*b*) Induction Method. This method may be employed to advantage with asynchronous machines. If the stator of an asynchronous motor is supplied with the rotor winding open, abnormal humming will usually occur particularly in the case of a short in the stator or rotor turns, while the currents in the three phases will also be unequal. If the short is in the rotor and the latter is turned, a marked fluctuation in the current strength can be detected on an ammeter connected to any of the stator leads as the short-circuited coil moves round. As

many variations occur per revolution of the rotor as there are poles in the motor. In addition, the movement of the rotor is jerky. If the short occurs in the stator turns, the same observation can be made for the rotor current if the rotor winding is supplied with a suitable voltage when the stator winding is open and the rotor is turned. An abnormal temperature rise in the affected coil can usually be observed. Moreover, measurement of the three voltages at the rotor terminals shows considerable differences, e.g. when supplying the stator and with a short in the rotor. A supply voltage, 50 70 per cent of the rated voltage, is usually sufficient to allow the fault to be recognized.

(*c*) Resistance Measurement Method. If in the case of d.c. machines the position of the fault in the armature cannot be determined by the temperature rise, e.g. if the motor no longer starts up, it may be found by resistance measurements, the procedure being as follows. The armature winding is supplied with d.c. of 10 20 per cent of the rated current through two suitable leads mounted on two segments, one pole pitch apart. The current strength is maintained constant, and the voltage drops measured with a sensitive voltmeter between every two adjacent bars, e.g. 1–2, 2–3, 3–4, etc., as depicted in Fig. 21 for a 4-pole winding. These voltages may be somewhat greater in the vicinity of the leads than at a certain distance on account of the current distribution. The differences are, however, small. In the case of most bars the segment voltages are almost equal, provided there is no short in the turns between them. A short is recognizable from the fact that the voltage between two bars is considerably smaller, being frequently almost zero. If a short is not found in the first pole-pitch, measurement should be repeated across the next pole pitch, and so on. The above mentioned inequality in the segment voltages is obviated by intermediate measurements, that is, by shifting the leads only half a pole pitch, e.g. from position *A*–*A* into position

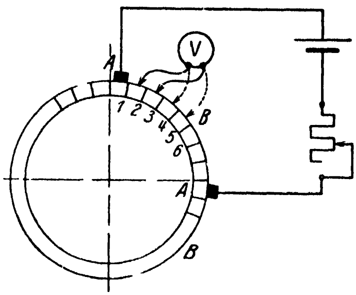


Fig. 21 Locating a Short Circuit between Turns in a D.C. Armature by Measuring the Resistance

B–B. If the number of bars cannot be exactly divided by the number of poles, connection should be made to the nearest bar. Measurement can also be carried out with a.c. instead of d.c.

For finding with speed and certainty shorts between turns of field windings, it is advisable to use a.c. instead of d.c.

To indicate the voltage conditions 0–10 turns of a total number of 118 turns were short-circuited and the voltage drops of the individual poles measured on each pole coil of a 6-pole synchronous generator. The following table gives the results—

Total Voltage (V.)	Current (A.)	Voltage of Individual Poles						No. of Short-circuited Turns in Pole No. 6
		1	2	3	4	5	6	
726	22·35	123	121	124	120	121	122	0
722	23·65	123	127	130	127	122	99	1
725	24·9	125	132	134	133	125	60	3
725	25·9	127·5	141	140	140	128·5	51	7
725	26·5	130	141	140	140	128	47	10

A short covering so small a number of turns might not be revealed with d.c., whilst considerable differences in voltage occur with a.c.

Rotating field systems should be removed for measurements of this kind, since under certain circumstances dangerous voltages may be induced in the stator windings.

Instead of supplying the dismantled rotating field system the stator winding can, in the case of a built-in rotating field, be connected for a short time to a suitable source of current at reduced voltage. Usually 15–25 per cent of the rated voltage is sufficient, giving a current approximately the same as the rated current. The rotor field coils have e.m.f.'s induced in them by the stator field; if there is a short-circuited turn in one of the pole coils, a considerable current will pass and heat it up appreciably. In addition, the voltages can be measured in the individual pole coils and the affected pole detected by its smaller voltage. With this test high voltages may occur in the rotating field winding, and contact with parts of the winding is therefore dangerous.

The discovery of short circuits between turns which exist only while the machine is running, e.g. under the influence

of centrifugal force, as in the rotors of alternators, is more difficult. Unless whole coils are put out of action by the short circuit and can be recognized by the difference in temperature rise, results can only be obtained with d.c. during operation by extremely careful measurement of the resistance when sufficient turns are short-circuited for the resistance to drop by a small percentage. In testing, the rotor winding is supplied across the slip-rings with as constant a d.c. voltage as possible. Starting from standstill, the resistance is continuously plotted from the current and voltage at different speeds. The voltage is measured at the slip-rings by means of specially mounted auxiliary brushes made of copper gauze. (If the voltmeter were connected to the current-carrying brushes, the variable contact voltage would considerably affect the accuracy of measurement.) An abrupt change in the resistance will be detected as the speed increases. In addition, other resistance measurements are necessary during running, in which only individual groups of poles are measured. For this purpose either an auxiliary slip-ring must be employed, or the shaft and an auxiliary brush C used as indicated in Fig. 22. Measurement is first of all carried out between the slip-ring A and the auxiliary brush C, for which a connection between the poles 1 and 2 and the shaft is arranged. This connection is then shifted to the poles 3 and 4, and so on until the affected pole has been found from the abrupt change in the resistance of one group of poles which occurs when the machine is run up to speed. If no change manifests itself when the connection 2–3 is made with the shaft, and an abrupt change in the resistance occurs with the 3–4 connection, the fault is in pole 3.

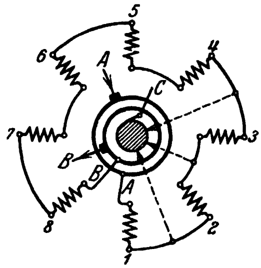


FIG. 22. LOCATING BY RESISTANCE MEASUREMENTS A POLE SHORT CIRCUIT OCCURRING ONLY WHEN RUNNING.

(*d*) REPAIR OF SHORT CIRCUITS BETWEEN TURNS. The stator and rotor coils of a.c. machines, and the rotor coils of commutator machines, in which there is a short in the turns should always be replaced. The insulation of the windings is usually so damaged by overheating that the risk of further shorts exists even when it is possible to find the points of contact and to insulate them. Field coils of thin wire,

provided the short has any disturbing effect at all, should be partially unwound and rewound. Bare copper field coils can be repaired fairly easily by re-insulating them. If the core has also suffered in the burning of the coils, any fused parts in it should be repaired. The reader is referred to Chapter III, para. 1 (*b*), on the investigation of unsound cores and their repair.

7. Open-circuited Windings. (*a*) CAUSES OF OPEN CIRCUITS. The chief causes of open-circuiting in windings and winding connections are mechanical, such as the fracturing of conductors due to fatigue caused by vibration where they are insufficiently supported for example, fractures of commutator necks—damage to the conductors due to careless handling, or open-circuiting at contact points of comparatively high resistance due to the melting of the solder. This latter defect may occur in the coil ends of the rotor windings of d.c. and a.c. machines, as well as in a.c. stators when the winding is overloaded. The risk is particularly great when the cross-section of the soldered joint is smaller than the conductor cross-section and when the overload is temporarily very high.

(*b*) RESULTS OF OPEN-CIRCUITING. The results of open circuits affecting the voltage production of generators or the starting up and running of motors are described in detail in the appropriate chapters. When there is open-circuiting in the armature winding of a commutator machine, e.g. where a soldered joint has melted, the commutator exhibits characteristic sparking, with a green appearance owing to the burning of the copper. The segments adjacent to the open circuit are burnt at the edges, the groove between the segments being blackened with carbon to the base.

8. Faulty Connection of Windings. Errors of this kind only occur when machines are not tested either at the manufacturer's works or after repair. The various possible wrong connections in the exciting and main circuits of generators and motors are mentioned in the appropriate sections.

A.c. stator windings having the connections of the individual coils of a phase reversed are a good example of this type of trouble. In series-connected windings the only symptom during no-load is the reduced voltage of the phase. A crossed connection can be easily detected by measuring the individual coil voltages and the whole phase voltage on no-load. When, however, two or more branch circuits of a phase are connected

in parallel, considerable noise and vibration occur even on no load.

In the case of a.c. motors, the starting may be impaired and abnormal noise and vibration due to the unbalanced current consumption may be observed. In order to discover a faulty connection of this kind, it is best to supply the rotor with a suitable voltage with the stator winding open, or conversely the stator when the rotor winding is open, and then to measure the induced voltages in the coils and phases.

9. Electro-magnetic Forces. Overloads, due to switching on and off, or on the occasion of a short circuit, may cause con-

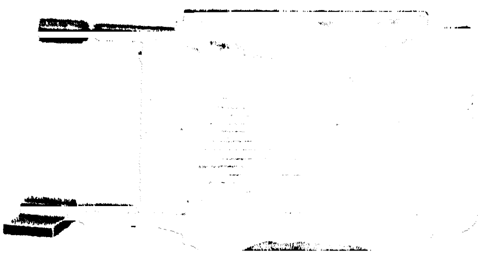


FIG. 23. MAGNETIC FIELD EFFECTS OF SHORT CIRCUITS ON THE TURNS OF AN INTERPOLE COIL OF AN OLD TYPE OF 750 kW. CONVERTER

siderable forces between adjacent conductors. Inadequately secured portions of the winding such as the coil ends of a.c. stator windings, the connections of damper windings, the conductors of field coils, etc., may become temporarily or permanently deformed. The coil ends of stator windings are forced against the stator iron, adjacent coil layers as well as the conductors of different phases being mutually repelled, and the conductors of one and the same phase mutually attracted. Unless these movements of portions of the winding and of individual conductors are restricted to a minimum by means of suitable distance pieces, the insulation cells may be fractured and the winding insulation be worn through by friction, resulting in breakdowns to earth and short circuits. In modern machines such defects hardly ever occur, as suitable supports for the winding are always provided. Fig. 23 shows the effects of a short-circuit current on the interpole coil of a 750 kW. rotary converter of an early type; in Fig.

24 are shown the results of very frequent short circuits in the stator winding of a 12 000 kVA., 3 000 r.p.m., three-phase turbo-generator formerly used for short-circuit tests. The coil supports were in this case inadequate.

Shafts, couplings, and attachments of rotor bodies may be damaged by the torque surges occurring on short circuit. Fig. 25 represents the half coupling and key of the above-

FIG. 24. MAGNETIC FIELD EFFECTS OF SHORT CIRCUITS ON THE STATOR COIL ENDS OF AN OLD TYPE OF 12 000 kVA. 3 000 R.P.M. TURBO-GENERATOR

mentioned generator; key and keyway have been hammered slack.

Electromagnetic forces may cause sparking on loose terminals on the terminal bar or at bad contacts, which give rise to stray voltage surges so that eventually short circuits between parts of the installation or breakdowns to earth occur. These stray surges may lead to breakdowns to ground and to short circuits due to flash-overs between turns in the phase end coils. Many troubles can, after exhaustive investigation, be traced to sparking.

10. Corona Effects. In the normal operation of alternators and a.c. motors, discharge phenomena are usually only met

with on machines of early design having rated voltages of over 10 kV., and then only in the form of glow discharge. Glow discharge is only visible at night in the form of luminous points, and only at places where the discharge extends farthest into the air, e g at points where the conductors emerge from the core. The presence of ozone caused by glow discharge can also be detected here and there in the cooling air. As little as 0·0002 per cent by volume of ozone in the air can be detected by anyone with a keen sense of smell The ozone content in the cooling air of old types of generators may, however, increase to ten times this value without the smell of ozone being strong or any danger to the insulation being suspected If the coil insulation, particularly the portion in the core, which is often wrapped with a mica product, has been carried out so carelessly that pockets of air are included, corona discharge may occur in these pockets.

FIG. 25 KEY AND KEYWAY DAMAGED DUE TO SHORT CIRCUITS

In the case of old machines for high voltages, no precautions were taken to avoid corona discharge at the end of and inside the slots. Accordingly it was possible for the pressboard slot liners, used for mechanical protection between the coils and the slot walls, to be destroyed. Fig. 26 shows an example of this The places least affected correspond to the positions of the cooling ducts. Similar effects of corona discharge on the paper backing of mica-paper wrapped coils are shown in Fig 27 The mica wrapping itself is unaffected.

As a rule, maintenance staff are unduly apprehensive about the consequences of corona discharge. Actual cases of trouble due to this are extremely rare and generally restricted to machines of early design.

The windings of modern high-tension machines are frequently provided with conducting layers at the slot ends as a

protection against corona discharge. Slot linings of pressboard and other materials are also coated with conducting varnishes.

FIG. 26. SLOT LINING OF PRESSBOARD DESTROYED BY CORONA DISCHARGE.

(Taken from a 16 kV single phase generator with single pole earthing after 12 years service.)

FIG. 27. COVERING LAYER OF A MICA WRAPPED COIL ATTACKED BY CORONA DISCHARGE.

(Taken from a 16 kV single phase generator with single pole earthing after 12 years service.)

CHAPTER III

TROUBLES IN THE CORE

1. Short Circuits in Punchings. (*a*) CAUSES AND CONSEQUENCES OF SHORT CIRCUITS IN THE PUNCHINGS. The core stampings of stators and rotors are covered with thin paper or are provided with a layer of oxide or varnish for insulation. This insulation may be bridged by a conducting layer due to formation of a burr if the punchings are machined with unsuitable tools, or due to the rubbing of the punchings when the rotor touches the stator iron. The iron losses are increased in this portion by the formation of eddy currents, and usually cause a higher temperature rise in the affected parts. Short-circuit currents may also flow, as illustrated in Fig. 28, along the pressure bolts of the core when these are not insulated. The magnetic flux enclosed by the loop induces the short-circuit currents, which increase the losses still more and consequently the temperature rise in the affected portions.

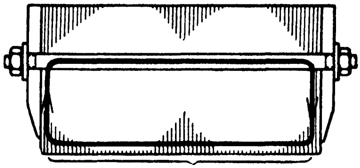


FIG. 28 FORMATION OF A SHORT CIRCUIT IN THE STATOR CORE OF A GENERATOR

The results of temperature measurements in the iron at the back of an old 900 kVA. 8 000 volt, $66\frac{2}{3}$ r.p.m. three-phase generator with faulty punchings are shown in Fig. 29.

The points at which the increased temperature rise in the iron occurred coincide with the points at which the punchings are most burred over on the air gap.

(*b*) IDENTIFICATION AND REPAIR OF A SHORT CIRCUIT IN THE PUNCHINGS. A stator or rotor made up of punchings can be tested by the following method for defects in the iron in which, owing to the destruction of the insulation, the stampings come into contact with one another. A number of turns are wound round the iron as shown in Fig. 30, and alternating current is passed through this provisional exciting winding for between a quarter and half an hour. Eddy currents which heat up the points affected are produced by the magnetic flux

occurring in the iron at the points where the punchings are insufficiently insulated. These points can easily be found by feeling with the hand.

The number of turns in the winding is determined approximately from the following formula—

$$T = K\,(D_m/I)$$

in which D_m in cm. the mean diameter of the iron ring,

I in amperes = the permissible or available current

and K is a constant whose value varies from 8 to 10.

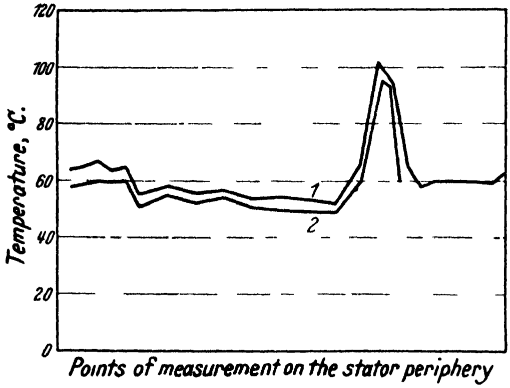


FIG. 29. TEMPERATURES IN THE CORE OF A STATOR, WITH IRON TROUBLE, OF A 900 kVA. THREE-PHASE GENERATOR

(1) Running at the rated load (2) On no-load at the rated voltage

This formula holds good for 50 cycles and a mean induction of 10 000 gauss. The necessary voltage V in the coil is given by the equation

$V = 4{\cdot}4 \times f.B.a.T.\ 10^{-8}$ volts in which

f denotes the frequency in cycles,

B the induction in gauss, and

a the minimum cross-section of the active iron in cm.².

$$a = 0{\cdot}9 \times l\,.\,h \text{ cm.}^2,$$

where l in cm. = the length of the iron less the widths of all the radial ducts, and

h in cm. = the depth of the cross-section.

If we assume f to be 50 cycles and B to be 10 000 gauss, then $V = 0{\cdot}022.\ a.T.$ volts.

The elimination of troubles in the iron is difficult when the burred layer is very thick, as may be the case when the rubbing has been extensive. Very serious burring renders partial rebuilding of the core necessary under certain circumstances. Small burrs may be removed with a sharp file and careful lifting with a chisel of the individual laminations. The procedure to be adopted in chiselling is shown in Fig. 30. Burnt places due to breakdowns to the core and short circuits between

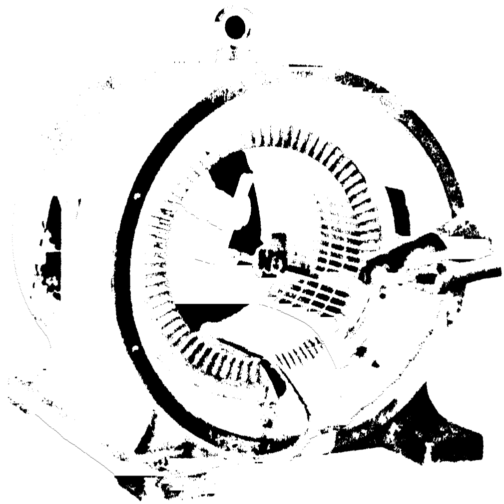


FIG. 30. ARRANGEMENT OF AN AUXILIARY WINDING FOR MAGNETIZING THE CORE
(Chiselling out faulty places in the punchings)

winding turns may be repaired by chiselling or machining away the affected parts, and then re-insulating the individual punchings from one another by paper or coating with varnish.

2. Noise. In addition to the well-known magnetic humming or "singing" of the machine, rattling noises, which usually disappear when the machine is unexcited, may be detected occasionally. On closer investigation the point of origin of the noise can usually be limited to a fairly small area. Vibrating distance pieces between the packets of laminations or vibrating end punchings are often found to be the cause. It is not uncommon to find small quantities of powdered rust at

the points concerned. This is always a sure sign of iron parts having become worn and rubbed on one another. Accumulations of rust of this kind may also be found at the points of junction in stators having several sections, when the noise is abnormal or in the case of vibration.

Loose distance-pieces can often be wedged with non-magnetic material, but care should be taken that the wedges inserted cannot gradually come out into the air gap. Vibrating pressure fingers or end-plates can likewise be wedged, welded or entirely removed.

3. Pulling-over of the Rotor. If a round rotor is mounted eccentrically in a round, or for that matter, out-of-round, stator, no vibration or whirling of the rotor will occur as a rule. The eccentricity, however, increases the unbalanced magnetic pull. This may result in additional deflection of the shaft and also in the deflection of the stator, and in the worst cases, the rotor may foul the stator. If, on the other hand, the stator winding of a motor or a generator has parallel groups of coils and an unequal air gap due to the displacement of the rotor, unequal voltages and in consequence circulating currents may occur in these parallel circuits. These cause an increase in the noise and sometimes vibration.

If an out-of-round rotor is mounted in an out-of-round stator, pulling-over of the rotor may occur. In the case of slow speed vertical machines a lateral oscillation of the exciter-commutator and of the slip-rings also occurs when the shaft pulls over in the guide bearings. These oscillations disappear when the machine is unexcited The corresponding places in the stator and rotor can be found by marking the shaft with a coloured pencil and measuring the air gap. It is desirable to apply to the manufacturers in these cases, since either rotor or stator defect, or possibly both, must be removed.

CHAPTER IV

TROUBLES ON SLIP-RINGS AND BRUSHES

1. Ring Material and its Defects. The design of slip-rings and the materials from which they are made varies in accordance with the electrical and mechanical stresses to which they are subjected in service. In addition to rings which are shrunk on to special bushes or directly on to the shaft with mica sleeves or similar insulations, a large number of designs has been brought out in which the rings are screwed on to a hub or held in position by through bolts. Shrunk-on rings are usually of bronze, cast iron, or steel; copper is also used in addition to these materials for screwed-on rings, particularly when special designs for passing very high currents are involved. Brass is usually only employed for slip-rings in the case of small motors.

Troubles may arise due to defects in material, when bronze or cast iron is used, for cast slip-rings. The rings may have blow holes or even channels, or, as a result of irregular cooling, places of unequal hardness and different structure. In consequence, the running surface may gradually wear away unevenly; "flats" then occur and cause vibration of the brushes. Forged steel rings or rolled or drawn copper rings are more rarely subject to these troubles, although differences in the hardness may also arise in them due to irregular cooling. In the event of such troubles as the formation of grooves, defects in the material of a ring can only be detected externally when large inclusions, porous places, or cracks are visible. Micro-photographs and hardness tests must be made on the dismantled rings if no other explanation is possible, but the necessity for this seldom occurs.

2. Brush Material, Pressure and Current Density. Brush material employed nowadays may be divided into four main groups—

1. Hard carbon (carbon, retort carbon, and coke).
2. Electro-graphitic carbon (the same basic material but graphitized electro-thermally).
3. Natural graphite containing various other materials.
4. Metallic graphite (graphite and metal with binding agents).

The manufacture of the various brushes is described technically in special literature on this subject.* Hard carbon brushes are not, as a rule, used on slip-rings; electro-graphitic carbons on the other hand are employed on steel rings if the speeds of rotation are not excessive. Highly graphitic brushes are particularly suitable for use on steel and cast-iron slip-rings, as well as on high-speed copper rings. Metal-graphite brushes are nowadays chiefly used on bronze and copper slip-rings for speeds of up to 6 000 ft. per min. and even higher. The various types of metallic brushes are distinguished from one another by their metal content, which facilitates the choice of a suitable brush even for difficult conditions such as high speed and high current density.

The maximum permissible current density in amperes per in.^{2} of active brush surface depends on the quality and dimensions of the brush, as well as on the material, dimensions, and speed of the ring. Accurate data in this connection are supplied by the manufacturer either of the machine or of the brushes. Soft graphite and electro-graphitic brushes can carry a load of 50–80 A. per in.^{2} and metallic brushes of 65 105 A. per in.^{2} The higher the density, the better must be the mechanical bedding of ring and brush. As a rule brushes of small surface area can be more heavily loaded than large brushes, due to the better cooling and better bedding on the ring. Only brushes carrying current intermittently, that is, when brush lifting devices are fitted, can be subjected in the brief period of operation to an appreciably higher load.

Brushes behave differently with alternating current and direct current in regard to wear and sparking, since in the latter case the effect of polarity arises (see para. 6).

The brush pressure chiefly depends on the material and speed of the brush and rings. As a rule, pressures of 1·7–2·25 lb. per in.^{2} are sufficient for natural graphite and electro-graphitic brushes and of 2·1 3·1 lb. per in.^{2} for metal-graphite brushes. The correct pressures are usually given by the manufacturer of the machine or of the brushes. The pressure should remain unchanged during the life of the brush and brushes mounted on the same ring should not differ in pressure by more than about 10 per cent.

3. Sparking. Sparking at the brushes may vary in appear-

* W. Heinrich *Das Bürstenproblem im Elektromaschinenbau* (in German). P. Hunter-Brown's book, *Carbon Brushes and Electrical Machines*.

ance. That occasionally occurring in the form of a streamer of constant intensity is usually harmless. it may be due to the expulsion of carbon particles. Frequent sparking of this kind of a reddish, blue to greenish white colour, as well as pin-point sparking, suggests trouble in the current collection. and gradual destruction of the ring surface and increased brush wear may be expected.

Among the reasons for sparking at the brushes, the chief one is out-of-round rings, causing vibration. This may occur as the result of distortion of the rings and displacement on the bush; or when the rings have not been properly shrunk on in the first place and have become loose when heated up in service. The same fault might appear if the initial shrinking was inadequate and the rings became overheated through using unsuitable brushes. "Flats" on the rings will also cause the brushes to run unevenly. Further data concerning pitting on the surfaces of rings are given in para. 6.

Water, acids, and other liquids reaching the stationary rings may produce pits on the contact surfaces and cause the brushes to vibrate during operation. The result of this is sparking, burning of the rings and frequently "flats." Mechanical damage, as from blows on the surface of the rings, naturally has similar effects.

Burning over the entire periphery of the surface occurs when the brush-gear is subject to vibration, of which the causes are not in the ring surface itself. It may be due to loose brush-holders or to slackening of screws or shrinkage of the insulated parts, or to vibration of the whole machine due to an error in balancing or the rotor striking the bearings in an axial direction, so that the brush gear, which is frequently mounted on the end shields or pedestals, vibrates. In addition, the transmission, e.g. belts or gear wheels, is capable of causing indirectly through the machine, vibration in the brushes and sparking. The brushes may overhang the edge of the rings axially in the case of excessively narrow rings or incorrectly mounted brushes, as shown in Fig. 31. Under these conditions, with the slightest axial displacement of the rotor the brush receives a blow and sparking occurs.

Incorrect brushes are another cause of sparking, when the friction between brush and ring may have bad results. As a rule the surface of the rings quickly becomes polished when suitable brushes are employed. It is, however, by no means

rare for the surface to be eroded, and the friction to assume such dangerous proportions that grooving develops. The brush will never run smoothly on such a ring but will commence to spark owing to the vibration. An unsuitable type of brush may also result in excessive contact losses and overheating of the ring without actually forming grooves. Unequal distribution of the current in the individual brushes then occurs quite often, with the result that brushes are overloaded and disintegrate. This process is dealt with in detail in para. 4. In addition, too great or too low a brush pressure may lead to similar troubles, as it affects the friction between ring and brush. Grooves, sparking, and eventually burning, may occur owing to contamination of the rings and brushes by oil which is either lost by the bearings or exudes from spaces containing oil vapour when the machine is running. Occasionally rings are unnecessarily lubricated.

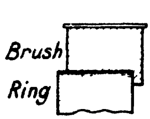


FIG. 31
INCORRECTLY MOUNTED BRUSH WITH AN AXIAL OVERHANG.

Sparking at the brushes may also occur when they are jammed in the holders or worn to such an extent that they rest on the holder.

The design of brush holders has, of course, considerable influence on the satisfactory operation of the brushes. Modern designs of various types ensure good running provided the right grade of brush is used, which should be free in the holder but not have too much play. The brush should not be tilted or jammed if the correct pressure on the ring is always to be maintained.

4. Unequal Current Distribution. This trouble means that only one or a few of the total number of brushes on a slip-ring is carrying the greater part of the current. At first sparking is observed only at the more highly loaded brushes. Unless the current is quickly equalized, however, the brush flexible tails may overheat during a lengthy period of operation and the soldered joints in the brush capping become overheated and run out; finally even the brush tails may fuse. The overheating of the brush tails, which are usually of copper, is recognizable by the bluish-yellow colouring they assume. If they are actually burnt out and the trouble is not attended to immediately, current flows through the brush holder and the walls of the box into the sides of the brush. In extreme cases, the brush holder may fuse or become completely welded

to the brush. As an example of this, Fig. 32 shows a scorched highly graphitic brush which ran on steel rings. Owing to an oxidized point of contact in the brush capping, the current flowed partially through the holder to the brush; the carbon parts were consequently damaged. The adjacent brush exhibits metal inclusions which resulted in unequal distribution of the current and which became clearly visible due to oxidation during the subsequent operation of the brush. The brush always

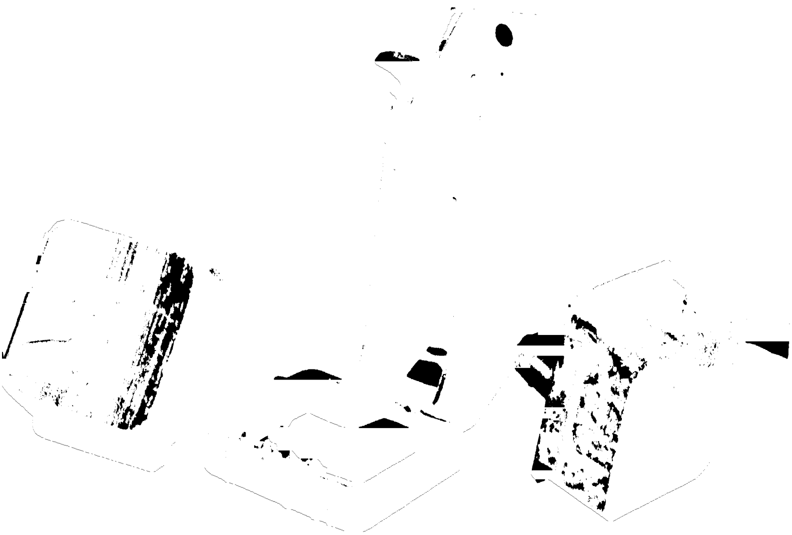


FIG. 32. *Right*: BRUSH AND HOLDER DAMAGED BY UNEQUAL CURRENT DISTRIBUTION. *Left*: METALLIC INCLUSIONS IN THE BRUSH SURFACE

wears away rapidly when there is unequal current distribution for any length of time, often within a few hours. An increased temperature rise occurs on the slip-rings and they may become loose on the bush.

Unequal distribution of the current may be caused by unsuitable brushes or varied types of brush on the same ring. The latter is a serious mistake. If two types of brush with different contact voltages, e.g. metallic and graphitic brushes or metallic brushes with different metal contents are employed, the current is distributed inversely proportional to the contact voltages of the individual brushes. In the first instance the metallic brushes would carry the major portion of the current

and be greatly overloaded since they possess a smaller contact resistance than graphitic brushes. The distribution of the

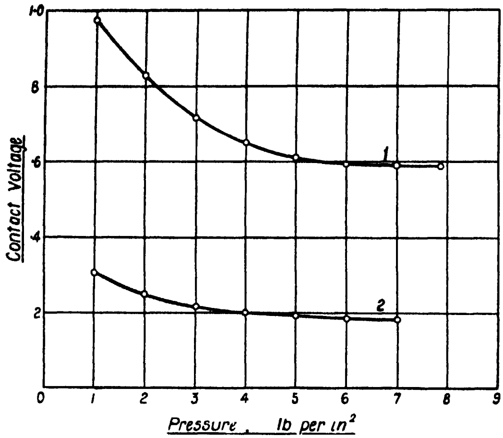


FIG. 33. RELATION BETWEEN CONTACT VOLTAGE AND BRUSH PRESSURE WITH CONSTANT CURRENT DENSITY AND SPEED

(1) Highly graphitic brush (2) Brush with high metal content

current in the brushes is regulated by the voltage drops in the brushes themselves, the drop between brushes and ring, and that along the brush arms. If brushes with a high contact voltage, i.e. graphitic brushes, are employed the voltage drops in the brush arms are usually negligible. Conversely, these drops in voltage may influence appreciably the distribution of the current in the parallel brush circuits, if brushes with a high metal content and very low contact drops are employed.

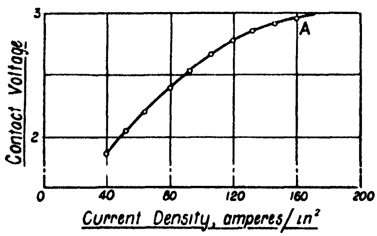


FIG. 34. RELATION BETWEEN CONTACT VOLTAGE AND CURRENT DENSITY OF A BRUSH WITH A HIGH METAL CONTENT

2 1 lb per in.² constant pressure.

Inequalities in the manufacture of brushes, and differences in pressure and length affect the contact voltage and consequently the uniform distribution of the current. A higher metal content and a higher brush pressure result in smaller contact drops. Fig. 33 shows the dependence of the contact drop between brush and ring on the brush

pressure. The contact voltage increases with vibrating brushes and a badly ground ring surface may also affect it. If the current density of a brush is incorrectly chosen, the operating point may be at an unsuitable position on the current/voltage curve. Fig. 34 shows this curve for a metallic brush. In the case of high current densities, somewhere in the range A, the contact voltage only increases slightly with the current density. A brush so highly loaded is no longer capable of suppressing or controlling an increased current load, since this requires an increasing contact voltage. In the example, this remains practically unchanged even with an increased load.

The voltage drops in the brush arms and leads are usually small, since these are liberally dimensioned. Fig. 35 shows a design with a parallel current connection. If the cross-section of the connections is inadequate, unequal voltage drops may cause unequal distribution of the current, and the brushes in the vicinity of A accordingly take more current than those at a greater distance. The cross-sections of the connections are therefore often graduated, particularly in designs for very heavy currents.

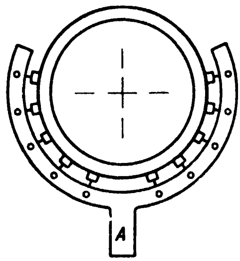


FIG. 35 SLIP RING WITH PARALLEL CIRCUITS FOR THE BRUSH CURRENTS

Considerable accumulation of dust in consequence of greater wear occurs from overloading on brushes with a high metal content, although in other respects these are less sensitive to high overloads than highly graphitic brushes, since the metallic particles, copper, bronze or brass, assist conduction. In metallic brushes with a fairly high graphite content the procedure in the case of current overloads is as follows: In the first place, graphite begins to accumulate on the surface, whereupon the contact voltage increases and the temperature rises (Fig. 36). The negative temperature coefficient of the brush then reduces the resistance and voltage drop, so that the current increases still further. Finally the brush is worn away. Sparking usually occurs when there is considerable local overloading of a brush. Small beads of fused metal form on the rings and increase the friction, and finally they become so rough as to grind down the remaining brushes. The brush tails become so hot during this process that their contacts are oxidized and the contact resistances increased. Finally, therefore, the current in the

affected brush may be considerably reduced or entirely cut off. owing to the fusing of the brush tails. The other brushes are then subjected to excessive loading and the trouble extends to these, so that the machine can no longer be kept in service.

The cure for unequal current distribution may easily be deduced from the description of the causes given above or from suitable tests. When the first signs of unequal distribution of the current are observed— for example, overheating of the brush tails, or heavy wear of the brushes it is often possible to avoid a stoppage by treating the rings with pumice stone or other abrasive. The brush surface is improved by slightly roughening the surface of the rings and in particular by the

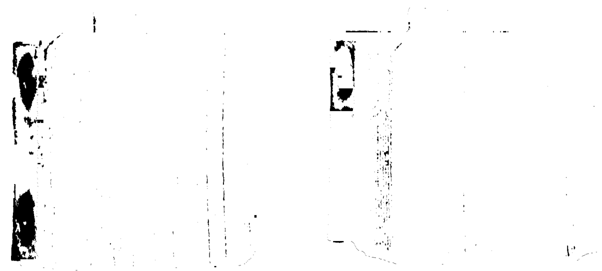


FIG. 36 ACCUMULATION OF GRAPHITE IN THE SURFACE OF METALLIC BRUSHES

Left Whole surface thickly coated with graphite
Right Surface partly pure metal recognizable by its brightness

abrasive matter deposited on them, and the current will probably be once more equally distributed. This is, of course, only an emergency measure. If the trouble increases or recurs, more drastic action is necessary, such as adjustment to a higher brush pressure which is as uniform as possible, or modification of the entire brushgear.

5. Development of Grooves. If the ring and brush materials are suitable, the pressure correct, and the rings are running true, the surfaces of the rings of a new machine quickly become polished and the brush surface smooth. Rings and brushes then operate satisfactorily indefinitely and the current distribution remains unaltered. Excessive ring wear manifests itself as a broad track or a fine groove (hair lines) or merely by the roughness of the ring surface. Fig. 37 shows metallic brushes with hair grooves. The causes may lie in the ring or brush or in both. The ring may be a faulty porous casting, not

turned cleanly, or out of true The brush material may have an incorrect metal content, may contain impurities, or may not be homogeneous, or the brush may be operating at the wrong pressure and with excessive friction. The actual passage of current from ring to brush may be responsible, due to unsuitable current loading, unequal distribution of the current and the resultant accumulation of brush dust and increased friction, as well as burning of the ring surface

Dust or grit conveyed by dirty air are the chief extraneous causes of trouble

The discovery of the basic cause is often difficult and requires at times special investigation. Rings which have become

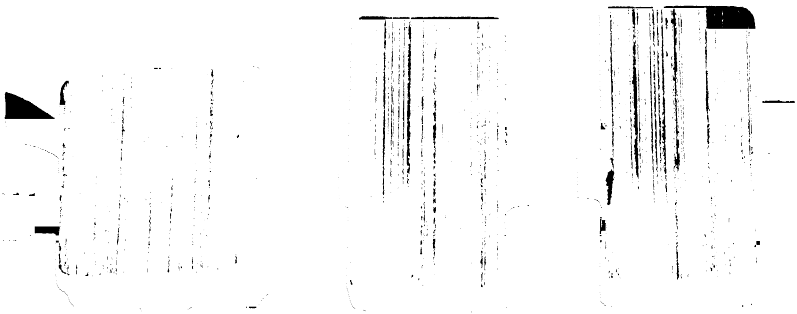


FIG. 37 METALLIC GRAPHITE BRUSHES WITH HAIR CRACKS

grooved should first be properly turned and polished, and the brush-gear then tested for correct pressure. The play of the brushes in the holders and their vibration should then be checked, and repairs carried out if necessary to obtain perfect mechanical conditions of rings and brushes. If no reason for the trouble can be detected, another type of brush should be used for these rings after informing the maker of the machine or brushes of the difficulties experienced and acting on his advice.

6. Pitting of Rings. In using certain natural graphite brushes, pitting may be observed occasionally on the rings after standing for some time, chiefly on steel rings. This occurs electro-chemically due to damp surrounding air and presumably with the assistance of heat. The polished surface of the ring underneath the brush is attacked to a more or less marked degree according to the period of standing. When

put into service later, the points attacked soon become black and rough on account of the sparking of the brushes. After a more lengthy period of service and progressively greater sparking, the ring exhibits eroded and flat places. To cure this a different grade of brush must be used, or direct contact between ring and brush must be prevented by means of a paper insert when the machine is shut down.

Pitting may occur on the slip-rings of rotary converters when the brushes are so arranged that the maximum value of the alternating current passes at the same point in the ring and in the same direction from the brush to the ring at every revolution. The ring is thus continually more highly loaded at one point. Such points may become rough in time, and eroded places may develop so that the brushes when running over them will spark. This trouble is avoidable by correct arrangement of the brushes. Similar phenomena may occur at the slip-rings of the rotating fields of single-phase generators under the action of the alternating current which is superimposed on the exciting current.

It may be observed in individual cases on the slip-rings of synchronous generators and motors carrying direct current that only the positive ring possesses a polished surface, whilst the negative ring is dull, and even rough in exceptional cases. The cause of this is the conveyance of particles of metal by the current from the negative ring to its brush; and the action is more pronounced with higher current densities. The simplest remedy is to change the polarity of the rings from time to time. Otherwise the wear of ring and brushes of negative polarity may be uneven, particularly with copper and bronze rings, though less so in the case of steel rings.

7. Excessive Brush Wear. The normal degree of wear must be known in order to estimate whether the brush wear is excessive. Alternating current tests on bronze rings show that on good metallic carbon brushes with a density of about 77 A. per in.^{2} and a speed of 5 000 to 6 000 ft. per min., wear of the order of 0·16 to 0·28 in. per 1 000 hours of service may be expected. With direct current of about 90 A. per in.^{2}, similar figures for wear are obtained on the same type of rings and with good metallic brushes as mean values for both directions of current. It should, however, be observed that brushes with the current flowing from ring to brush show much greater wear than those when the current flow is in the opposite direction.

In a series of tests with different makes of brush the ratio of the wear of those on the negative poles to the wear of those on the positive poles was found to be between 2 and 10.

Less wear than the above values was obtained with copper rings and good brush working conditions, as well as with graphitic brushes on steel rings under similar conditions of operation. Wear naturally depends largely on the attention given to the rings, the dimensions of the brushes, and the copper content of the rings, as well as on the speed, current density, pressure and cooling. Individual brushes on the same ring may exhibit different degrees of wear. The cause for this may be lack of uniformity in manufacture, or a greater or less degree of any of the disturbing influences previously described. A brush which works in a perfectly satisfactory manner at a speed of 2 000 to 2 500 ft. per min. at high loadings, may completely fail when this speed is doubled.

The arrangement of the brushes on the ring greatly influences wear. Cooling is hindered on rings with closely spaced brushes, and the dust from one brush may be carried along under the contact surface of the succeeding one. The brush wear is therefore greater than on rings with widely-spaced brushes. In order to expel the dust and cool the surface better, brushes are sometimes slotted obliquely or transversely to the direction of movement. Brush wear may also be greatly increased by external dust. The same effect is produced by incorrect treatment of the rings, viz. frequent use of emery cloth, or use of unsuitable lubrication. Only with really suitable brushes and careful maintenance of rings and brush-gear can wear be kept at a minimum. Any one of the above troubles immediately produces marked brush wear far exceeding the values mentioned at the beginning of this section. Unequal distribution of the current is by far the most common cause of brush wear.

When there is considerable brush wear the cause of trouble should be sought among those described above, and eliminated by the methods suggested.

8. Care and Maintenance of Slip-rings. Provided suitable brushes are employed, slip-rings and brushes, as a rule, require no attention, apart from the occasional removal of dust, light rubbing with emery cloth of rings which have become pitted, and the replacement of worn brushes. Occasionally lubricants such as vaseline or oils—sparingly employed—improve the

conditions of operation. Great care should, however, be exercised in the use of lubricants, even those highly recommended and sold at exorbitant prices, as they often do more harm than good.

The rough surface of a ring which is still round can usually be reconditioned without difficulty with a suitable abrasive and emery cloth It is, however, not possible by these means to cure a ring which is out of round; in fact, abrasion will merely aggravate the trouble as flats and cavities become still more extensive. Out-of-round rings can only be renovated by trueing with a tool or by means of special grinding equipment with a rigidly clamped stone. Before turning, the rings should be tightly secured to the shaft.

In order that no carbon dust may penetrate beneath the leads and connections and cause creepage paths and flashovers, the spaces between the rings should be packed with cotton tape or the like. Turning should only be carried out with a small feed of about 0·002 in. to 0·004 in. per revolution in order to obtain a smooth surface The peripheral speed may then amount to about

40	52 ft.	per min.	for	cast-iron and steel rings.
65	100	,,	,,	bronze rings.
100	165	,,	,,	copper rings.

Any good tool steel may be used for turning. The ring should be turned without interruption; particular care should be taken to see that the play in the lathe gearing is not too great, which would result in unevenness in the turned surface. After turning, the rings should be polished if necessary with emery cloth mounted on a suitably curved piece of wood.

9. Mounting of the Brushes. Brushes should always be carefully mounted and bedded in. In inserting the brushes the brush holders should be carefully checked for correct position, cleaned of dust, and the pressure lever and its pivot tested to see they are not sticking. The distance between the lower edge of the brush box and the ring should not exceed 0·08 in. and the holders should be so mounted that the brushes do not project beyond the edges of the slip-rings. If the width of the ring is greater than the width of one or more adjacent brushes, the brushes on the individual arms should be staggered in order that the ring may wear as uniformly as possible over the entire width. The brushes should not be tight in the holders, and special care should be taken to see that the brush tails do

ot impede the movement of the brushes. The clearance of the brushes in the holder should normally not exceed the following values—

	Clearance (Thousandths of an inch)		
	In Longitudinal Direction (Axial)	In Direction of Rotation (for a brush width of) 0·2 in. to 0·625 in	Over 0·625 in
Minimum clearance	8	4	6
Maximum clearance	20	12	16

Excessive clearance is just as harmful as too little, since the brushes rock in the holder and a proper running surface is not obtained. The differences in the spring pressures of all the holders of a brush arm should not amount to much more than 10 per cent, or unequal distribution of the current will occur. In addition, the brush pressure should remain as constant as possible throughout the entire working range.

The brush surface should be ground to fit the curvature of the ring with glass paper or emery cloth of medium grain. This is placed between the ring and the brush as depicted in Fig. 38; the pressure lever of the holder is then mounted and the strip of glass paper moved backwards and forwards until the entire surface of the brush is bedded. Metallic brushes are more difficult to bed than graphitic brushes, owing to their hardness. These brushes, however, can be prepared with a file or suitable grinding wheel from a template corresponding to the curvature of the ring. Brush manufacturers may also in the case of large orders supply the brushes ready shaped. Brushes and rings should be carefully cleaned of dust after bedding and the machine is then again ready for service. It is advisable always to mount and bed-in the brushes carefully, as then the chances of subsequent trouble are much less. When changing and renewing brushes during service not more than

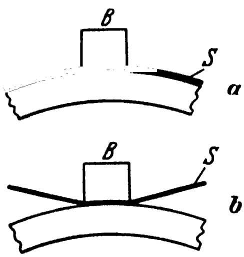


FIG. 38

GRINDING IN OF BRUSHES

S. Emery cloth or glass paper.
B Brush
(a) Correct method.
(b) Wrong method

about one-third of the entire set of brushes should be renewed at the same time, so that the old brushes will collect the current satisfactorily while the new brushes are bedding themselves in. Complete renewal thus proceeds without any marked change in operation.

CHAPTER V

TROUBLES IN COMMUTATORS AND BRUSHES

1. Definition of Good Commutation. The development of electrical machine construction in recent times has led to a demand for the maximum possible electrical loadings. This also applies to commutation, in which the limiting conditions are approached in the case of modern d.c. machines. The old idea that not even the smallest sparks should be visible at the brushes of d.c. machines at any load, including when possible overload, has accordingly had to be abandoned. Modern ideas are authoritatively expressed by the Verband Deutscher Elektrotechniker's 1930 *Rules for Electrical Machines* (*REM*) as follows: "Operation may for practical purposes be described as sparkless when commutator and brushes remain in serviceable condition." If, therefore, only periodical cleaning of the commutator, replacement of worn brushes and slight lubrication of the commutator are necessary, and service is not interrupted, the commutation may be described as good even if slight sparking is to be observed. Practice also shows that large machines for heavy currents can remain in continuous full load operation for months on end with slight pin-point sparking, without any brush or commutator trouble. Machines with a very varying load and brief very high current overloads, such as are used for traction, winding and rolling mill equipment, are even less sensitive in this respect. During brief high current peaks, there is no time for the full effect of sparking at the brushes to be felt, the surfaces of brush and commutator become repolished during the succeeding light load periods, and the brushes cool off in the meantime.

2. Adjustment of Interpole Strength and Polarity. The reader is assumed to be familiar with the processes in commutating an armature coil, as a fundamental explanation is beyond the scope of the present work and numerous textbooks on the subject are available. Alteration of the direction of the current in the coil short-circuited by the brush and in the adjacent coils produces in the former a reactance voltage. The interpoles are used to balance this reactance voltage at all loads. The correct connection of the interpole is shown in Fig.

39. The strength of the commutating field is usually adjusted to the proper value at the manufacturer's works. If, in exceptional cases, it should only be possible to carry out this adjustment when the machine is placed in commission, the work is usually carried out by the manufacturer's staff. In order to test interpole adjustment or commutation it is necessary, in addition to the other investigations, to plot brush potential curves, work usually done by the works test staff, not so much because of the arrangement and carrying out of the test as on account of the evaluation of the diagrams recorded.

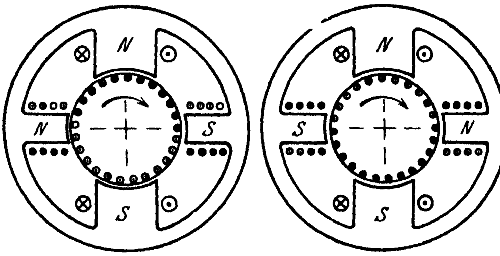


FIG. 39 CORRECT POLE SEQUENCE IN D.C. GENERATORS AND MOTORS

Left Generator *Right* Motor

This requires great experience if reliable conclusions are to be drawn as to the correct or incorrect interpole adjustment, and practical suggestions are to be made for the modification of the commutating field.

Nothing can be observed on a d.c. machine when in operation which clearly indicates incorrect adjustment of the commutating field except marked sparking. If this is suspected as the cause of the trouble whether after a change of brush grade or brush width, or after permanent alteration of such operating conditions as voltage or speed, it is advisable to consult the manufacturers of the machine. The latter will modify the commutating field by arranging a parallel resistance to the commutating winding, or by varying the air gap by means of inserts in the pole body or between the body and the yoke.

3. Ageing of the Commutator. A commutator should remain as round as possible in service independently of the temperature and speed. The bars should not be deformed by heating and centrifugal forces, and should not project either singly or in groups, since the brushes will then be inclined to

chatter. The slightest modification to the commutator parts influences its condition and dimensions and, in addition, commutators, particularly large ones for high speeds, only reach their final state after a certain period of service in which all variations cease. Commutators frequently require to be turned after trial runs at the manufacturers in order to remove the slight deformations which have arisen due to heating and cooling. Even after being in service for a fairly lengthy period, in which the commutator ages, a second turning is often necessary. Many firms "season" their commutators artificially by frequent heating and cooling, heating being effected by friction on the running commutator.

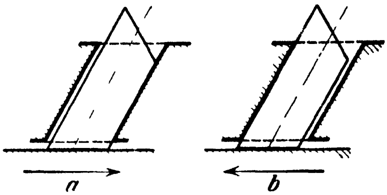


FIG. 40. MOUNTING OF A REACTION BRUSH HOLDER

(a) Correct inclination for direction of rotation indicated

(b) Incorrect inclination

4. Brush Holders. With accurately made radial holders, the brushes should operate satisfactorily regardless of the direction of rotation. With inclined or reaction holders, however, a predetermined direction of rotation must be maintained. Fig. 40 shows the correct and faulty mounting of a reaction holder. There is no ideal inclination of the brushes for all commutators and it varies in degree with different constructions.

The brush boxes, particularly for soft brushes, must not be too short, or they may cut into the brushes and cause them to stick. Sideways clearance between brush and holder is also important if chattering of the brush in the holder is to be avoided, and at the same time accurate bedding of the brush on the commutator is essential. The limits of play allowable are given in Chapter IV, para. 9.

The brush pressure has to be adjusted principally according to the grade of brush and the speed. It is important for the brush pressure to be kept the same over the whole working range of all the brushes, particularly on machines for high currents which have a large number of brushes per arm.

Some constructions allow of an adjustment of the pressure during the wear of a brush, but with a properly designed brush holder this is not necessary. The maintenance staff may vary the brush adjustment according to their own ideas and do

more harm than good. In general, reduction of the pressure by not more than 10 per cent to 15 per cent from the new to the used state of the brushes is quite practicable, and the difference in pressure for different holders should also not exceed this value. Between the pressure finger and brushes of many holders there is an insulating piece, or alternatively this may be placed at the fulcrum of the pressure finger. If it has become defective, the spring and pressure piece may act as conductors of the current, which will probably lead to trouble.

The holders should be firmly fixed on the brush arms and the brush-gear so constructed that the brushes do not vibrate. Cross connections and brush arms, particularly for heavy current machines, must be adequately dimensioned so that no oxidation occurs owing to excessive heating at the contacts. Oxidation increases the contact resistance and causes the currents to be unequally distributed to the individual brush arms. These contacts, as well as the connections of the brush leads, should always be well bedded during overhaul of machines.

5. Brush Material, Pressure, and Current Loading. It is customary nowadays to use carbon, in one or other of its forms, for brushes on commutators, and metal-graphite brushes are only used for machines of very low voltage. Carbon brushes can be divided roughly into three groups—*hard carbon*, *soft carbon*, and *electro-graphitic*.

As a rule hard carbon brushes are only suitable for speeds up to about 3 000 ft. per min. and current densities from about 25 to 50 A. per in.^{2} They have a high specific resistance, high brush contact drop, and are generally used for machines of small output, as well as in cases where difficult commutation conditions require a brush of high contact drop. A.c. commutator machines are also usually equipped with hard carbon brushes. This type of brush has a tendency to chatter, especially when the machine is on no-load; on this account brush fractures often occur with even a slight roughness of the commutator surface.

Highly graphitic, i.e. soft carbon, brushes can be used for all purposes on d.c. machines. Their specific resistance is smaller than that of hard brushes, and, furthermore, the coefficient of friction, which is of the order of 0·1–0·2, is small. These brushes are suitable for commutator speeds up to about 10 000 ft. per min., and facilitate quiet running.

Electro-graphitic brushes are intermediate between soft carbon and hard carbon brushes. They are used to-day for all types of commutator machines, and according to the grade are suitable for average and high commutator speeds up to 10 000 ft. per min. Their coefficient of friction, specific resistance and brush contact voltage are higher than those of soft brushes. They are at the same time less inclined than hard carbon brushes to chatter when running without current.

Metal-graphite brushes are only used for machines with high currents and low voltages on which commutation is easy and good; for example machines for electrolytic purposes. The brush contact voltage is small, varying between 0·3 and 0·6 volts according to the metallic content, so that the brush contact loss is small. The highest permissible peripheral speed is about 5 000 ft. per min. The specific brush pressure for hard carbon, electro-graphitic and highly graphitic brushes should be between 1·5 and 2·25 lb. per in.^{2}, but in exceptional cases may be as high as 2·5 lb. per in.^{2} for stationary machines. For vehicle motors which are subject to jolts and vibration, even higher pressures are necessary. Metal-graphite brushes show excessive wear with too low brush pressure on account of unequal current distribution, and therefore for these a pressure of about 2·5 lb. per in.^{2} is desirable.

6. Causes of Sparking. (*a*) CHARACTER OF SPARKS. Sparking occurs in different forms and colours according to the nature and extent of the trouble responsible for it, and first becomes injurious when complete layers and areas of the brush surfaces are burnt. It is generally called *pin-point* sparking when in the form of small spherical sparks. There is, however, another type of sparking referred to as *streamers*. Slight pin-point sparking, which often occurs on the leaving brush edges in the form of small blue-white or reddish points, is the least harmful. Larger pin-points, particularly when yellow in colour, suggest commutator trouble and eventually blacken the commutator. When pin-point sparking and streamers occur together, it is an indication of more serious trouble, the commutator becomes damaged in a very short time, and the brush surfaces show sooty streaks across the direction of rotation. A machine with vibrating brushes tends to exhibit pin-point sparking combined with streamers of a greenish-white colour. This indicates burning copper, and as the burning progresses, the sparking usually becomes so bad as to

produce a crackling noise, and occurs not only at the edges of the brushes but also under them. Streamers appear under the brushes and the latter seem to run on a cushion of fire. The brush contact surfaces no longer show a polish, but have sooty or dull spots of irregular shape, often in well-defined areas.

Glowing of the brush edges from time to time in conjunction with sparks and streamers indicates bad commutation and varying unequal current distribution under the brushes of the same arm. This condition must not be allowed to continue as it leads to deterioration of the brushes and of the commutator surface. The phenomena associated with sparking are so varied that precise determination of cause and effect is only possible to a certain degree, and even then only after considerable experience of the problem.

A.c. commutator motors generally show sparking of a reddish-white colour. They may exhibit a much higher degree of sparking than d.c. machines without damage.

(*b*) Brush Vibration. This is the cause of the most serious commutator troubles in service. The most likely reasons for this trouble are "out-of-round" commutators, high commutator segments, high mica segments, grooves and ridges in the commutator, or in fact, any unevenness of the commutator surface, however produced. At the higher speeds, at which the brushes can no longer follow the irregularities in the commutator, they will bounce and consequently spoil the quality of the commutation if the commutator shape is even slightly distorted due to projection of several copper or mica segments, It is sometimes found that recently cleaned commutators exhibit unequal polishing, in that single segments are unpolished on a commutator which is otherwise in excellent condition. Such segments or groups of segments standing back from the surface of the commutator, are called *flats* and result in small variations in the surface in contact with the brushes, making the latter run roughly. The greater the speed of the commutator or the more sensitive the machine as regards its commutation, the more important it is to have an absolutely round commutator. Consequently, the distortion arising in service in commutators as detailed in Chapter V, para. 3, must be a minimum. Apart from temporary distortion, however, the commutator can become permanently damaged as the result of burning or unequal wear of the surface. Temporary distortion of the commutator will occur with rapid

temperature changes, also with any sudden rise in the cooling air temperature. Permanent damage of the commutator contact surface naturally results in permanently defective commutation, while temporary distortion only affects it for a longer or shorter time according to the circumstances. If the distortion is due to heating, the machine will probably operate as well as before when the commutator has reached the new temperature corresponding to the new permanent state. If a permanent, although small distortion has occurred, such as a high segment or a flat, and this has increased the degree of sparking, the machine can still remain in service as long as single segments have not been burned or the brush contact surfaces damaged so as to cause streamers. Quite often in this case dark patches or streaks will form on the commutator.

Distortion of the commutator is best identified by running the machine, when in extreme cases it can be observed visually, by the movement of the brushes in the holders. Smaller brush movements can be felt with the finger tips by holding a fountain pen or similar piece of insulating rod on the top of the brush. Quite small distortions can be detected by this means. Protruding segments can be easily recognized owing to the chattering noise produced. In addition, the side surfaces of the brushes show traces of vibration, in that they become polished.

A less common cause of bad commutation is brush vibration due to an incompletely round armature; that is, the armature core may be displaced so as to give an uneven air gap. The armature is then subjected to an unbalanced pull towards one side, particularly with machines having a small gap. If there is considerable play in the bearings the armature tends to have a whirling motion, which is followed by the commutator and brushes. At a high speed this causes excessive vibration of the brushes.

Vibration of the brushes, brush holders and of the whole brush-gear can be produced by the knocking of segments on the brushes or from mere friction. If there is too much play in the holders, the brushes may "bounce" and cause movement of the brush holders or even brush arms until it is impossible to operate the machine because of the excessive sparking. The most likely causes of such oscillations are the grade of brush, shape of holder and its mode of attachment to

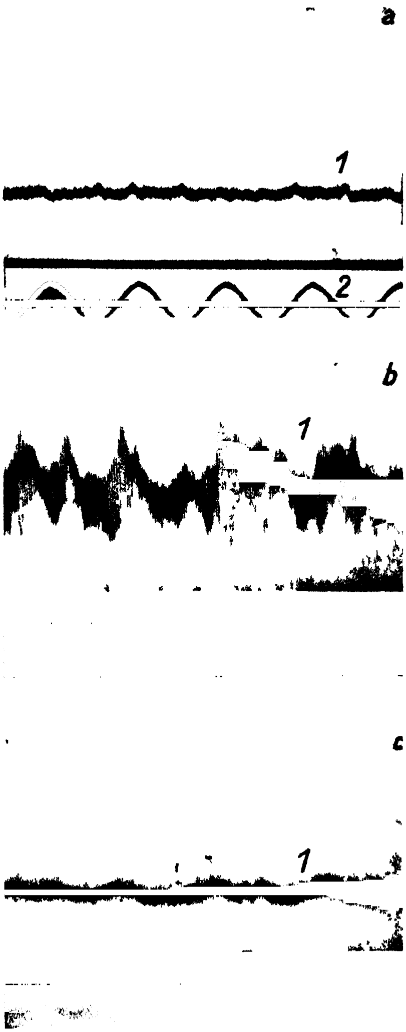


FIG. 41. OSCILLOGRAMS OF THE BRUSH CONTACT VOLTAGE

(a) Normal radial holder normal brush arm
(b) Experimental reaction holder normal brush arm
(c) Experimental reaction holder brush arm with additional support

1. Brush contact voltage
2. Timing frequency 50 cycles

the brush arms. The variation of brush pressure with wear, and the distance of the holders from the commutator, are other possible causes of bad commutation. Troubles from these causes are indicated by the state of polish on the commutator and brush contact surfaces. An example of this, showing how incorrect fixing of the holder on the brush arm increases the vibration, is shown by the oscillograms of the brush contact voltage in Fig. 41, taken between two separately supplied neighbouring brushes Fig 41 (a) is the normal brush arm with ordinary radial holder. While the oscillogram in Fig. 41 (b) was being taken a reaction holder with different dimensions was fixed on the same brush arm. For Fig. 41 (c) the same reaction holder was used but the brush arm had additional supports. Care is necessary, however, when using additional supports to steady brush holders if the results are to be successful.

The obvious signs of vibration caused by friction between commutator and brushes are that the brushes, even at no-load or small load, begin to squeak

and chatter. By running over the commutator surface with a dry cloth or by a very light application of paraffin wax, this noise and vibration can usually be reduced. This phenomenon, which depends on the state of the brush contact surface at no-load and when on load, is particularly common in traction motors. A large number of brushes is sometimes broken when running on light load (such as during the shunting operation of a locomotive) and certain brush grades are also prone to this trouble when new brushes are being run in with no load on the machine. The chattering can become so violent that parts break where least expected to do so. Fig 42 shows two such brushes. Fig. 43 shows brushes and brush holders damaged during normal operation of the machine by vibration due to use of the wrong grade of brush. The first cause of commutation trouble is often natural frequency vibrations due to the brush wear having reached a certain stage. The shortened brushes either fit unsatisfactorily in the holder so that they tend to stick, or else the relative weights and the friction in the brush box change, and with them the natural frequency. In spite of a steady or only slightly varying brush pressure the brushes begin to vibrate. If the brushes are replaced by new ones of the same grade, the machine may operate for a month or so without trouble until the critical brush length is reached once again.

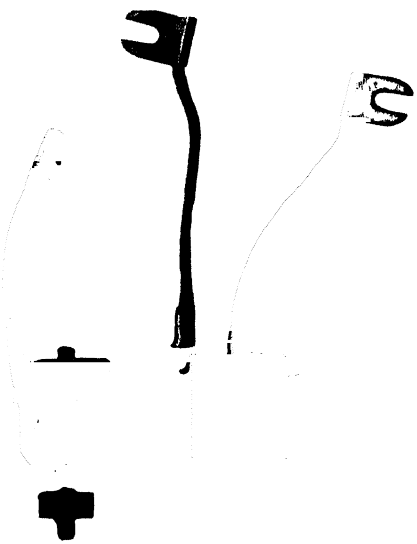


FIG. 42. DAMAGE TO BRUSH TAILS CAUSED BY VIBRATION WHILE RUNNING-IN BRUSHES AT NO LOAD

While vibration troubles have very different causes, the results are always the same: as soon as a critical stage is reached, commutation deteriorates. General directions for the cure of these troubles cannot be given except for cases

where the commutator is not completely round, or the commutator segments or mica project. If externally caused vibrations due to the driving and transmission gear are responsible, they can usually be recognized and cured after careful observation. Natural frequency vibrations are more difficult to investigate If these are suspected to be the cause of the trouble, and other possible causes have been removed, an

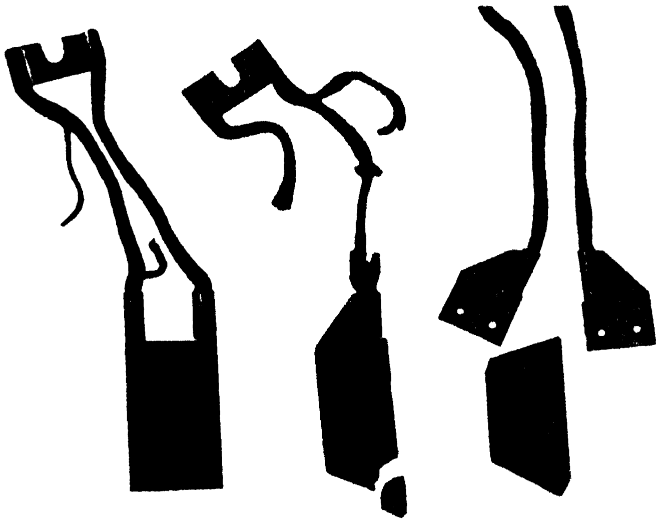


FIG. 43 DAMAGE TO BRUSHES AND BRUSH TAILS AT NORMAL LOADING, CAUSED BY VIBRATION DUE TO USE OF THE WRONG GRADE OF BRUSH

alternative grade of brush should be tried. In every case it is advisable to consult the supplier of the machine. If the trouble is attacked in the wrong way in the first place, matters may be made very much worse.

(c) INCORRECT INTERPOLE ADJUSTMENT. The achievement of proper interpole adjustment and the possibilities of altering it in service are discussed in Chapter V, para. 2.

When the interpole is wrongly adjusted, the machine sparks on all brush arms, even on partial load. The sparking becomes more intense the longer the machine is worked, until it is impossible to operate it at all. A machine will often on account of its construction and dimensions operate for a considerable

time in spite of wrong interpole adjustment, particularly with a variable load. In this case, there is frequently slight sparking accompanied by burning of the segments; and the surface of the commutator, especially when running, appears to be covered with a greyish film. The brushes, according to the strength of the interpole excitation, acquire on either the leading or trailing surfaces dull stripes, known as *zones* as in

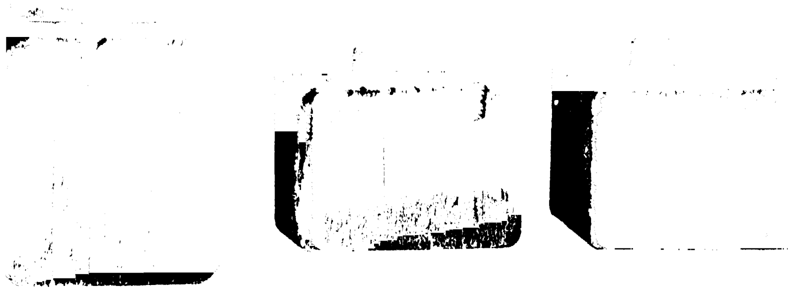


FIG. 44 DAMAGED ZONES OF THE CONTACT SURFACES OF SOFT CARBON BRUSHES DUE TO WRONG ADJUSTMENT OF THE INTERPOLE FIELD

Fig. 44, which at first are only faint but become more defined as the machine continues in use. It needs considerable experience to judge when incorrect interpole adjustment is the cause of the trouble, since this zone-formation also occurs in connection with vibrations.

If the brush width is changed, it must be noted that a brush which is narrower, i.e. spans fewer segments, needs a stronger interpole field, and vice versa.

(*d*) REVERSED INTERPOLE WINDING. If a machine develops violent sparking at no load or very light load, the interpole winding may be wrongly connected, a trouble only likely to arise after repair or overhaul. In this case, the connections to the interpole winding should first be checked. Terminals to be connected together are usually marked. The poles should be as shown in Fig. 39, and the trouble is most quickly put right if the connections attached to the brush leads are interchanged and the machine retested.

(*e*) INCORRECT BRUSH POSITION, SETTING IN NEUTRAL. The brushes of modern d.c. machines having interpoles generally lie in the mechanical neutral, or are only slightly displaced from it, and the best brush position is usually indicated by a

mark on the brush rocker-ring. If it becomes necessary to check the brush position, this can be done in the following way.

With the armature open-circuited and the machine at rest, the main pole winding is supplied from an external source—for example a storage battery—with a small current, through a switch so that the circuit can be easily closed or opened. Between two adjacent brush-arms a sensitive d.c. voltmeter is connected, having a scale of a few volts. If the circuit is quickly opened or closed, voltages are induced which are at their smallest value when the brushes are in the neutral zone. This position must be established by rocking the brushes, and the test should be carried out with two or three different armature positions. This method is frequently termed determining the *kick-neutral*.

Another method is as follows

With the main field circuit broken, the armature and interpole windings are supplied with current of about one-tenth normal value. The brush rocker is then displaced, always in the same direction, until the armature of the machine begins to turn, and this position is noted. The same procedure is repeated for the opposite direction and the new point marked. The test is repeated several times with the current constant, and the neutral zone lies almost exactly in the middle between the two points found. During this test, compound windings must be disconnected, and the brush rocker must not remain displaced for long after the armature has commenced to rotate, since it may very rapidly reach a dangerous speed. This experiment at the same time allows the connection of the interpole winding to be checked, since the displacement of the brush rocker must be in the same direction as the armature rotation.

For reversible motors, the neutral zone can be very precisely fixed from the speed variation as described in Chapter XII, para. 2 (*g*). This last method is usually known as determining the *running neutral*.

(*f*) WRONG GRADE OF BRUSH. When the commutation of a machine alters after new brushes of the same grade have been fitted, this usually indicates that the new brushes have not been properly bedded, and consequently, as the brushes become bedded in, the commutation tends to revert to its former standard. If, however, the new brushes are of a different grade and the commutation continues to be unsatisfactory,

even though the contact surfaces of the brushes are run in, it may be concluded that the quality of brush is not suitable for the machine in question It is naturally advisable to use the same grade of brush as was originally supplied.

It is always bad practice to use different grades of brush simultaneously on a machine, and particularly on the same brush arm. If in cases of emergency odd brushes are used, these must at least be uniformly distributed on brush arms of the same polarity

(*g*) INACCURATE BRUSH SPACING. If individual brush arms are spaced irregularly round the commutator, then those armature conductors connected in parallel by brushes of the same polarity are not in the same strength of magnetic field, and circulating currents which arise may cause sparking on single arms. One cause of this trouble is the shrinkage or removal of the insulation of the brush arm; or it may be caused by faulty construction of the support or the brush holder. In addition, it occasionally happens that in certain designs all brushes of the same polarity are displaced in the machine as received from the supplier. In this case, however, as distinct from the inaccuracies mentioned before, the spacing between alternate brush arms is correct.

The theoretical spacing between adjacent brush arms is

$$\alpha \quad \frac{\text{Commutator circumference}}{\text{No. of brush arms}} \text{ inches.}$$

The actual distances between brushes measured on the commutator circumference as a rule ought not to differ from the theoretical figure by more than the thickness of one mica segment. The sensitivity of the machine to errors in the brush spacing varies. With incorrect brush spacing individual brushes may be inclined relative to the commutator and this may lead to chattering and ultimately sparking.

(*h*) BRUSH BOXES INCORRECTLY ASSEMBLED. If the brush boxes are carelessly built up on the brush arm, they may not be in a straight line, the total effective brush width is increased and the number of segments covered at one time varies, which adversely affects commutation. The brushes which spark are generally those fixed most wide of the electrical neutral position. When adjusting the mounting of the brush boxes, either the brush rocker should be displaced, or the armature turned so that all brushes are in line with one segment edge. If the

brushes of one arm were stepped originally, the brushes of each step must be arranged in one line with the commutator segments.

(*i*) Wrong Brush Pressure. With too small brush pressure, the brushes, especially when they are narrow, are vibrated off the commutator by the impacts of the segments and the changing friction. This leads to sparking and the current is then unequally distributed amongst the brushes. The brush pressure must be suitable for the type of brush as well as for the operating conditions of the machine, and a few guiding values are given in Chapter V, para. 5. The results of unequal current distribution are discussed in Chapter V, para. 7.

The original brush pressure may decrease due to heating up of the springs caused by unequal current distribution, or due to slackness of the springs produced by mechanical overloading. More often than not the operating personnel are responsible for this if holders with adjustable spring pressure are provided. With a properly constructed holder the pressure remains almost constant over the whole working range of the brushes. An alteration in pressure is not necessary and usually does not occur without some special reason.

(*k*) Unequal Air Gaps. Due to differing lengths of air gap under the various main poles, which may be caused by unequal pole lengths, the parallel armature circuits may have different e.m.f.'s induced in them, so that internal equalizing currents occur. For this reason modern machines, particularly for large outputs, have equalizing connections. Since even with the most accurate construction of the machine, small differences in air gaps and magnetic permeability are unavoidable, the equalizing connections prevent bad commutation by diverting the circulating currents from the brushgear. If, however, the differences in the air gaps are too great, or the equalizing connectors are lacking, or if insufficient commutator segments are connected to them, the circulating current flows through the brushes and commutator and spoils the commutation.

Considerable variations in the length of the air gap can occur due to displacement of the bearings, or to errors in the remounting of the poles after overhaul or repair. In addition, saturation plates between pole body and yoke may have been forgotten, or poles be inclined or alternatively displaced sideways, causing wrong flux distribution. The variation in the air gaps of single poles ought not to exceed 10 per cent of

the mean value. The pole spacing measured between the pole horns should not differ by more than 0·02 to 0·04 in. from one another.

Inequalities in the air gaps or in the spacing of the interpoles have similar results, and the extent of the permissible deviation is of the same order as for the main poles. It is important that the axes of the interpoles should be as nearly as possible midway between the main poles.

(*l*) Cross Connectors and Brush Arms having Unequal Resistances. Tarnishing and oxidation of contacts on the cross connectors which connect together the brush arms of the same polarity can prevent equal current distribution to the brush arms, particularly on heavy current machines and, as a result, the brushes of individual arms may spark. Such trouble is most rapidly detected by a close examination of the contact surfaces. Points of high resistance very often show discoloration due to heating. In this case, it is best to remove all connectors and contact pieces and give them a thorough cleaning.

The current may even be divided unequally among the individual brushes or brush groups on the same brush arm if the contact resistances are raised for the reasons stated above. Leads and brush-gear may also be faulty in construction as regards the current carrying contacts. Further details can be found in the technical literature on this subject.*

(*m*) Defective Windings. Short circuits in the main and interpole windings, breakdowns to earth at two or more places in a coil, and poles connected with reverse polarity all spoil the magnetic symmetry and have the same effects as inequalities in the air gap. The effects of earths and short circuits are described in Chapter II, paras. 3 and 5. Lack of magnetic symmetry, like unequal brush distribution, frequently only affects individual arms. The tracing of the primary cause is discussed in Chapter VI, para. 4.

Winding short circuits in armatures soon show up by spoiling the commutation and by burning the segments connected with the defective coils. An armature with badly soldered connections can, however, remain in service for a long time before the defects become apparent. Often the increase in resistance of a soldered joint—for example on the commutator

* W. Heinrich: *Das Burstenproblem im Elektromaschinenbau* (in German). P. Hunter-Brown's book, *Carbon Brushes and Electrical Machines*

leads or, in the case of bar windings, on the connection at the back end--is very small to start with. Only a machine with very sensitive commutation will show any appreciable sparking at once, but as progressive oxidation of the faulty soldered place continues, the symptoms become worse, and the segments directly connected with the faulty parts, and also those connected to the equalizing connections, begin to blacken and the sparking increases. If the commutator is cleaned and the burnt places ground off, the conditions are sometimes so improved that the machine will operate for much longer, although the faulty joint will inevitably melt out in time and make further service impossible, since the soldered place will then be almost a break in the circuit. When burnt segments are irregularly spaced, or else one pole or pole pair apart, the cause is probably short circuits in the windings, or faulty soldering. If no melted solder can be seen with the naked eye as evidence of melting, the fault can be detected by resistance measurements as described in Chapter II, para. 6 (c). If this is not successful, as sometimes happens with very badly soldered places, it is necessary to resolder all joints near the burnt segments. In the case of short circuits in the armature, the site of the short circuit is generally quickly found since it causes overheating, with the usual consequences.

Breakdowns to the iron in the armature only influence the commutation when they occur at two places and cause a section of the winding to be short-circuited. In a two-wire earthed supply, one breakdown to the iron is sufficient, and if the breakdown is of low resistance, then the circulating current may cause sparking. It is obvious that for all commutation troubles the armature winding insulation must be tested.

(*n*) SHORT CIRCUITS BETWEEN COMMUTATOR SEGMENTS. Short circuits may occur between adjacent segments and also between their leads, owing to the collection of carbon dust. These short circuits, especially in the case of machines with high voltage between segments, may cause single groups of segments to flash across and thus lead to sparking. When the short circuit has only a low resistance, the commutator joints may even become unsoldered, and in some circumstances the faulty segments can be identified by the discoloration due to heat. In the case of short circuits between the commutator segments, additional segments which are two pole pitches away will also be burnt, since they are electrically connected

by the equalizing connections. Occasionally commutator segment shorts are due to the ingress of acid to the mica insulation after soldering the connections with an acid flux, to unsuitable lubricant applied to the commutator, or to metallic foreign matter which has lodged in the mica insulation between the segments or in the mica vee-rings. Such troubles can prove to be very extensive, particularly when the short circuit is inside the commutator, which may then have to be dismantled. For all external commutator segment shorts the mica must be thoroughly scraped with a rotating cutter or a saw until it appears white. If this has not cured the trouble, the commutator must be unsoldered and the insulation between each individual segment separately tested with a testing lamp, or better still, with an insulation test box.

7. Unequal Current Distribution. Burning of Brush Leads. The brush leads of heavy current machines for continuous service for example, the type used in electro-chemical works may suddenly melt away or become heavily oxidized. In addition, the brush material may loosen and disintegrate, and in bad cases the brush boxes also occasionally melt away. Sometimes sparking develops, but it may happen that all this takes place without any sparking if the machine is not particularly sensitive with regard to commutation and if the overload capacity of the brushes is large. All the above phenomena are the result of unequal current distribution, and the stages by which the trouble develops are as follows. One brush by chance takes more current than the others and the brush contact resistance falls on account of the negative temperature coefficient. This in turn increases the current loading of the brush, which tends to disintegrate on cooling down. The resistance of the leads is raised by the overheating and the brushes and holders are damaged. The reaction of different grades of brushes to unequal current distribution varies. Soft carbon brushes are much more affected than hard carbon or electro-graphitic, particularly at low pressures. Fig. 45 shows several soft carbon brushes which have become so disintegrated by unequal current distribution, and the consequent current overloading, that they have eventually fallen to pieces. In this case, the cause of the trouble was too low brush pressure combined with the special susceptibility of this kind of brush to unequal current distribution. Fig. 46 shows the destructive effect of unequal current distribution caused

by the use of the wrong grade of electro-graphitic brush. The machine, of 400 kW. output running at 100 volts and 4 000 amperes, was operating day and night with practically no attention. The workman in charge of it had fitted unsuitable brushes on his own initiative. It can be clearly seen that after the burning of the brush tail, the brush box operated as a conductor of the current and finally, on account of this heavy

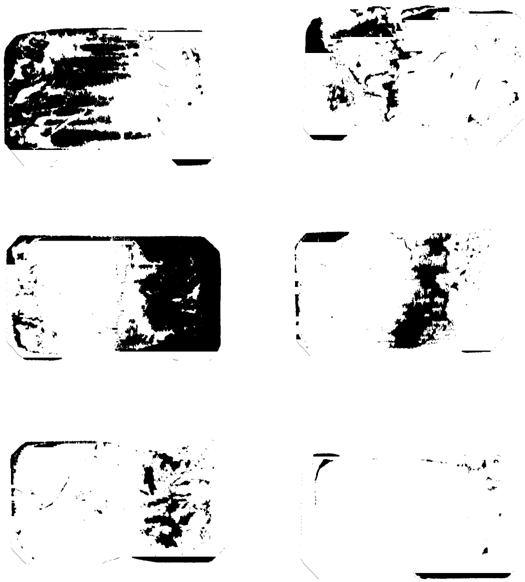


FIG. 45. DISINTEGRATION OF SOFT CARBON BRUSHES DUE TO UNEQUAL CURRENT DISTRIBUTION.
Pressure 1·85 lb. per in.². Current density 45·50 A. per in.².

current, melted away on the side where the brush rested in contact with it.

The first step to be taken in dealing with unequal current distribution is to examine all contact surfaces of the brushes and holders. The features to be looked for are oxidation due to overheating, faulty copper parts, and melting out of the solder from joints.

The difference in pressure of the brushes should not exceed 10 per cent of their average pressure. For soft carbon brushes, unequal current distribution cannot be avoided if the pressure is allowed to fall below 2·25 lb. per in.², but electro-graphitic

Fig. 46. Damage to Brush Levers and Holders through Unequal Current Distribution from Using the Wrong Grade of Brush

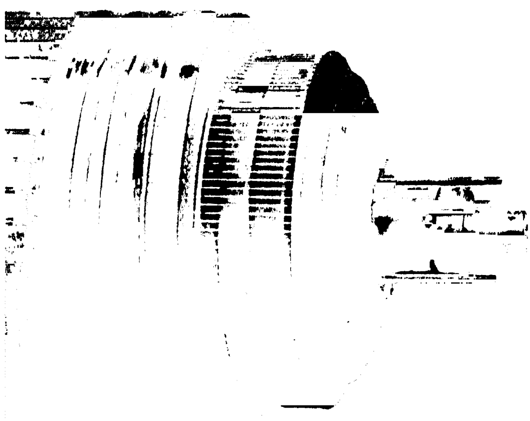


Fig. 47. Scoring of the Commutator Surface Due to One Row of Brushes Running without Current as a Result of the Two Brush Tracks having Unsuitable and Different Brush Grades

brushes will, of course, operate satisfactorily below this pressure. By way of experiment the specific loading of the brushes of one arm can be altered by the addition or subtraction of individual brushes. While it is desirable that the same grade of brush should be used for the whole machine, it is absolutely necessary for arms of the same polarity to have similar brushes.

The result of using different grades of brushes on a commutator is shown in Fig. 47, which illustrates the armature of a three-phase commutator motor. The owner in fitting a set of 36 brushes had used no less than three different grades. Although the brushes on the outer side operated fairly satisfactorily and ran quietly, the inner row consisting of a variety of unsuitable brushes tended to chatter. As a result the inner brush row was carrying no current and developed fractures of the brush tails, the current being collected only by the outer brush row. Abrasion and greatly increased friction of the brushes without current led to grooving on the inner part of the commutator, resulting in a track of varying depth over the whole circumference. In this case, the unequal current distribution did not cause burning of the brush leads, as the single row of brushes was adequate to collect the current On the other hand, the unloaded brushes vibrated and fractured. In the inner row 75 per cent of the brushes were broken, but the outer row had 95 per cent intact.

Fig. 48 shows how irregularities in the manufacture of brushes of exactly the same grade and from the same supplier are responsible for another kind of brush trouble. One row of brushes of the three phase commutator was from an old stock and the other from a recent supply. After the machine had been running for a short time the current was being unequally distributed and one row of brushes began to bounce, causing the other row to collect more current so that its brushes continued to run quietly. The almost unloaded row of brushes finally vibrated so violently that they broke, especially at the places where the tails were connected. In addition, the state of polish produced on the two brush tracks was quite different. The inner track which was carrying the current was evenly polished with relatively light grooving, while the outer track exhibited various areas and degrees of grooving.

If the trouble is treated early, the far-reaching effects of unequal current distribution can be prevented. The commutator should be periodically cleaned, with the brushes raised,

by rubbing with fine grained pumice stone, emery cloth, or glass paper, the two latter being applied on suitably shaped wooden pads. Unequal current distribution due to chattering of the brushes can be stopped by slight greasing with paraffin or vaseline. If, however, this expedient has to be employed too frequently, because the brushes and commutator quickly deteriorate again, it is best to change the brush gear so as to make the pressures and brush contact resistances correct.

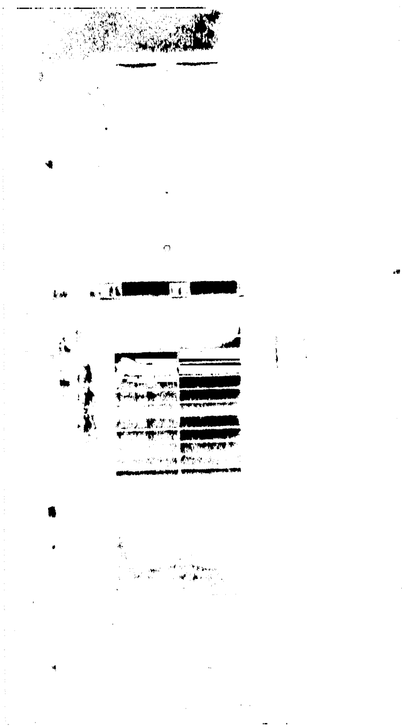


FIG. 48. AN EXAMPLE OF BRUSHES RUNNING UNLOADED AND FINALLY BREAKING DUE TO INEQUALITIES IN BRUSHES OF THE SAME GRADE

8. Commutator Grooving. Unequal wear of the commutator is known as *grooving*. According to the appearance they are variously called *furrows*, *hair lines*, *paths* or *tracks*, all of which arise from different causes. Wide, well-defined paths are chiefly due to unsuitable brush material at too high pressure and high commutator speed. The effect is then like the brush surfaces shown in Fig. 49. Also associated with this are hair lines like those shown in Fig. 37.

Light channels which cease to deepen after reaching a certain depth and after the commutator surface has attained a certain degree of hardness can really be regarded more as a lack of perfection than a trouble. For this reason, one must beware of turning or grinding the commutator solely on account of its grooved surface. The surface hardening of the copper which has taken place while the polish has been forming will be removed, and the commutator will merely become grooved again. New channels will form exactly as before unless the brush arrangement is altered.

The chief cause of grooving is use of the wrong grade of brush. Soft carbon brushes are themselves particularly prone to produce grooving on account of their mechanical polishing effect; hard carbon or electro-graphitic brushes are less inclined to cause trouble. Metallic brushes score the commutator and make considerable channels. Inequalities caused during manufacture will of themselves produce grooving. Other causes are bad commutation, wrong loading of the brushes, wrong brush pressure, mechanically bad running of the commutator, dust and sand, and abrasive dust left after using emery cloth, or oil and other lubricating media. The segment

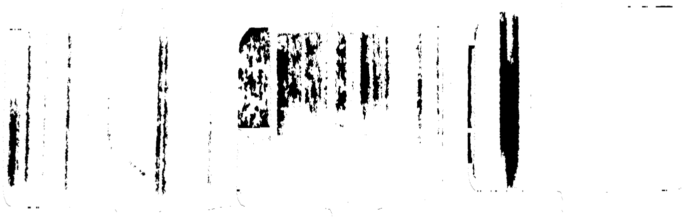


FIG. 49 BRUSHES EXHIBITING CONSIDERABLE GROOVING

copper occasionally causes channels if it is insufficiently hard or contains oxides. In addition, the deposition of copper on the brush contact surfaces owing to brush vibration or faulty commutation has a bad effect. Commutators turned with a badly ground tool or ground with a rough stone tend to form grooves sooner than those which have been subjected as little as possible to this kind of treatment. Commutators exposed to an atmosphere containing gas or acid sometimes show increased wear. The sulphur gases of coke ovens which also attack the contacts of switchgear, are particularly harmful in this respect.

Discovery of the cause of grooving is the most important step towards its elimination.

9. Excessive Brush Wear. Brush wear depends on the machine design and the operating conditions, and general rules cannot be given. The extent of brush wear in different circumstances can best be judged from actual examples. Electro-graphitic brushes on a 2 500 kW. machine in a chemical works, operating day and night, at a current density of 48 A. per in.^{2} and a commutator speed of 5 700 ft. per min., were

subject to an average rate of wear of 0.157 in. per 1 000 hours running. On d.c. machines of smaller output, up to about 100 kW., with current densities of 25 to 50 A. per in.^{2} and commutator speeds up to about 4 000 ft. per min., electro-graphitic and soft carbon brushes wore down between 0·020 in. and 0·08 in. per 1 000 hours running Metallic dust or sand lodging on the contact surfaces will naturally increase the wear. Heavy sparking due to bad commutation, current surges followed by streamers, short circuits, rough surface of the commutator from too frequent application of emery cloth, oil, grease and other lubricants all have a similar effect

Soft carbon brushes as a rule wear less than electro-graphitic brushes but are not so well suited for all purposes.

10. Overheating of the Commutator. The commutator losses which make themselves evident by the heating they cause are due to brush friction and contact drop. Their proportion to the total loss depends on the commutator speed, the state of the commutator surface and on the kind of brush used. If a commutator overheats according to *B.S S.* 168, 45° C rise is permissible for industrial machines —either one or both of these losses may be increased, particularly if the friction and contact drop have an unfavourable joint effect. As the polish forms on the commutator, the contact losses generally increase while the friction losses decrease. Recently-ground commutators have on the other hand less contact loss and more friction loss. Excessive commutator heating may also be caused by other troubles such as tarnishing and oxidation of the commutator contact surface—the latter may be due to the ingress of gases, as in a chemical works—bad commutation, rough commutator surface, too great brush pressure, or use of the wrong grade of brush. When the wrong brush grade is used the contact drop, and consequently the heating, may become excessive. The contact drop depends on many factors, current density and direction of current, condition of both contact surfaces, speed and brush pressure, as well as the general running conditions. Soft carbon and electro-graphitic brushes have a brush contact drop of between 1 and 2 volts, hard carbon brushes have even higher brush contact voltage. Metallic brushes have, according to their composition, a drop of from 0·3 to 0·6 volt. Fig. 50 shows the brush contact voltage when a machine was first put into operation and after it had been working for some time. The tendency of the polishing to

increase this voltage is quite noticeable. It is well known that the brush friction losses for hard carbon brushes, and to some extent for electro-graphitic brushes, also increase appreciably if the machine is running at or near no-load. Overheating of the commutator can therefore occur solely from no-load running, particularly when the brush friction losses constitute the main portion of the commutator losses as may be the case with high speed machines.

Troubles due to ventilation as detailed in Chapter I, para.

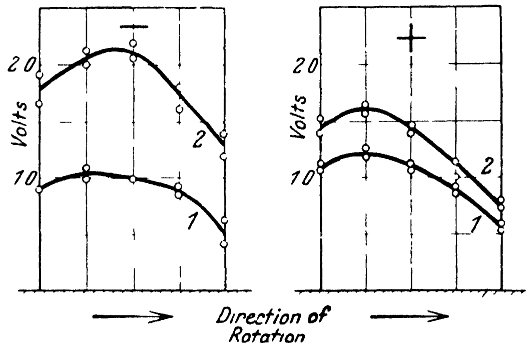


FIG. 50. CHANGE IN BRUSH CONTACT VOLTAGE DUE TO THE FORMATION OF POLISH ON THE COMMUTATOR AND BRUSH SURFACES

Curve 1. Commutator and brushes freshly polished with emery.
Curve 2. After 700 hours' continuous running with 70 per cent rated current.
The curves are the averages of measurements taken on two different arms at normal current. Specific current density = 6. A per in.^{2} Specific pressure 2.4 lb. per in.^{2} soft carbon brushes.

6 (*c*) and 6 (*d*) may also be responsible for excessive temperatures. When overheating occurs the first step is to examine the commutator and brush contact surfaces and to endeavour to find a suitable remedy according to their condition by experimenting with other brush grades. For example, a number of brushes of each polarity can be removed, an expedient which may prove successful where the friction losses exceed the brush contact losses.

11. Short Circuits and Flash-overs. In order to render short circuits as harmless as possible to the commutator, an effective protective circuit must be incorporated in the installation. For this, high-speed circuit-breakers are desirable which cut out a short circuit in the minimum possible time, and preferably before the currents have reached abnormal values. Where

such short circuits are liable to occur, it is essential to use those brush grades which can withstand the very high momentary overloads without emitting quantities of glowing carbon particles and thus aggravating the effects. Electro-graphitic brushes are particularly suitable and soft carbon brushes with increased resistance slightly less so. When sparking occurs, brushes that are too soft are quickly worn away against the commutator surface, which is pitted by the arcing in much the same way as if a file had been applied to it. The carbon dust produced causes a serious danger of flashover between brush arms. If suitable brushes are provided a machine can generally withstand a short circuit with very little sparking and without serious consequences, but if the brushes are wrong, trouble may ensue.

In addition, short circuits between the segments may cause sparking because of the collecting of carbon dust. This occurs as a result of using unsuitable brushes, insufficient cleaning of the grooves between the segments after bedding in the brushes, or after the commutator has been reground or polished with emery cloth. Machines with high segment voltage are naturally most affected as regards this. Therefore, after grinding the brushes or using emery cloth, the commutator should always be thoroughly cleaned by dry compressed air, and by undercutting the mica. Electro-graphitic brushes should always be chosen for machines with high segment voltage since they are less inclined to fractures or disintegration on overload than soft carbon brushes.

12. Maintenance and Repair of Commutators. Except for the regular removal of dust and dirt, and the cleaning of the grooves between the segments, no further attention to the commutator is necessary if suitable brushes are fitted. In a few cases, for example, machines of which the brushes tend to chatter owing to periodical no-load running, the commutator may be rubbed over with a dry rag or one with a small quantity of paraffin or vaseline. Lubricating substances should be sparingly and cautiously applied to the commutator, and many recommended lubricants for commutators contain quite useless ingredients. Bad commutation is frequently caused by these materials, since the commutators acquire a hard surface skin due to the residue of the grease settling on to the commutator contact surface and predisposing the brushes to vibration. Frequent use of emery is unnecessary except for the purpose

of removing burnt copper or carbon, due to sparking or short-circuiting, or for cleaning surfaces oxidized by gases. When the machine is running properly with suitable brushes, the appearance of the polished surface varies between reddish brown and dark red, although with special grades of brush a commutator may be running satisfactorily and still appear black.

When there are only small groups of high segments or flats, the grinding can be done with a hand stone. If, however,

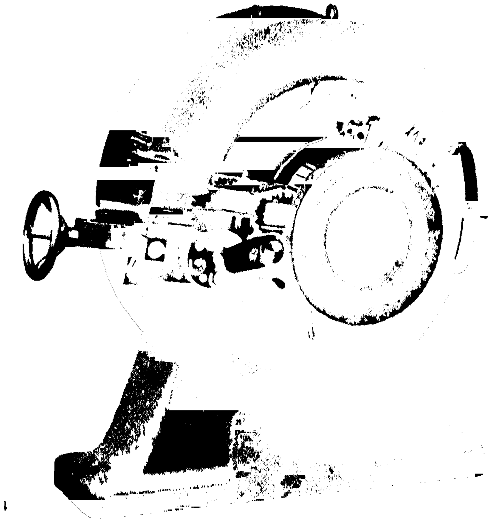


FIG. 51. COMMUTATOR GRINDING APPARATUS WITH FIXED STONE (Noriel patent)

the commutator is so distorted that the vibration of the brushes spoils the commutation it must be re-turned or ground. It can be re-turned either in its own bearings or in a lathe. In the first case, a well-mounted tool holder is necessary, and with undercut mica a maximum cutting speed of 200 ft. per min. should be used. On a good lathe a speed of 300 ft. per min. may be used, but with flush mica only about 100 ft. per min. Not more than 0·004 in. per revolution should be removed. Good quality hard carbon tool steel should be used.

For grinding, either a revolving grindstone or a grinding apparatus with a fixed stone may be employed. Fig. 51 shows

such a grinding set, as patented by Norrel, with an adjustable grindstone. Machines up to about 200 volts normal voltage can be ground under voltage with this apparatus. The grinding speed should be between 1 200 and 4 000 ft. per min.

Afterwards the grooves between the segments should be undercut with a suitable saw to bring the mica to the proper depth. The mica should not appear as in Fig. 52 (*a*), with sloping edges. Fig. 52 (*b*) shows the work properly carried out. The sides of the copper segments should afterwards be rubbed over lightly with a triangular file or scraper, and the whole surface repolished with a suitably shaped emery block or fine-grained pumice stone. All copper dust on the contact surfaces must then be carefully removed with a rag in order that the copper particles may not become embedded in the brush contact surfaces. Finally, the ventilating ducts located at the side of the running surfaces in many commutators must be carefully cleaned with benzine and if necessary relacquered. This cleaning prevents the short circuits between segments and commutator necks, which quite often occur on freshly ground commutators. The ingress of turnings and copper dust between the winding parts should be prevented by proper screening of the commutator necks with paper or cloth.

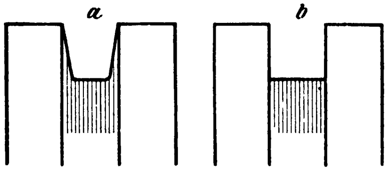


FIG. 52.
UNDERCUTTING OF COMMUTATOR MICA

Before turning, the pressure bolts of the commutator bush should be tested for tightness. Further tightening of the commutator, however, must only be carried out when there are loose bolts; excessive force must not be used or the segments would merely become displaced.

13. Mounting of the Brushes. The brush holders must be mounted as for slip-rings, i.e. they must be well fitted and the brushes must have the clearances indicated in Chapter IV, para. 9. If the entire breadth of the commutator is not occupied with brushes, they must be arranged as in Fig. 53 (*b*) so that the whole commutator face is equally used and tracking avoided.

The bedding in of the brushes is described in Chapter IV, para. 9. At the same time that the bedding and cleaning of

the brushes and holders takes place, the brushes must be run in on their contact surface. Machines with soft carbon brushes can be put on full load more quickly than can machines with electro-graphitic brushes since their contact surfaces become run in more rapidly. The latter must first be run on half load, and not until they have run for a few hours should they be subjected to full load. Many failures of electro-graphitic brushes can be traced to carelessness when first setting the machine in operation.

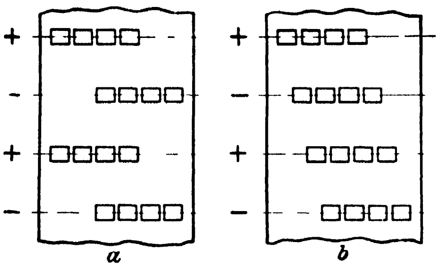


Fig. 53
Brush Distribution on Commutators

14. A.C. Commutator Motors. Most of the troubles already described also occur on a.c commutator motors. A special feature of these motors is the bad influence of harmonics on the commutation; and on account of the transformer voltage, which is injected from the main field into the coils undergoing commutation, only narrow hard carbon or electro-graphitic brushes can be used. Narrow brushes are, however, not conducive to quiet running, and the choice of the right brush grade is difficult On the other hand, commutators with suitable brushes will stand a much greater degree of sparking from alternating current than is the case with direct current. It is outside the scope of this work to describe all the different types of a.c. commutator motors and their commutation troubles. When serious difficulties arise, it is best to refer to the supplier of the machine.

CHAPTER VI

VIBRATION

VIBRATION of electrical machinery can either arise in the machine itself or be caused by driving or driven machinery, or the intervening transmission gear. Examples are the transference of vibration from turbines to generators in hydraulic and steam turbine sets, the reactions of the driven machines in heavy industry, such as occurs to the driving motors of rolling mills, stone crushers, etc., troubles due to transmission gear, unsuitable or badly fitted couplings badly aligned gears, pulley, rope and chain drives. The determination of the cause of the trouble in all these cases is difficult and it is usually necessary to isolate the machine and test it by itself. If, however, the machine is a separate unit for example, a rotary converter or phase converter the testing is simpler.

The real causes of the vibrations of a machine can be of different kinds but errors in balancing, and lack of magnetic symmetry as a result of winding defects, are the most common.

In this connection it must be noted that for single-phase generators vibrations due to the pulsating torque cannot be reduced below a certain value. The proper construction of the bedplate is the factor having most effect on the amplitude of the vibrations. The vibrations may increase in course of time, and in such cases the bedplate should first of all be examined for fractures and loosening.

The erection and bolting down play an important part as regards vibration with other machines, and frequently relatively small vibrations of badly installed machines can affect the surrounding structures and apparatus very seriously. In order to minimize this transfer of vibrations to neighbouring buildings, which is often necessary in residential areas, the machines can be "insulated" by suitable foundations from the other buildings. For this purpose, and also for acoustic insulation, various materials and types of construction have been evolved by firms specializing in this work.

1. Types of Out-of-balance. All rotating parts of a body with mass m, have a centrifugal force acting upon them. This may be calculated from the equation $P = m\,(v^2/r)$ lb., in which

$$m = \frac{w}{g} = \frac{\text{Weight in lb.}}{32{\cdot}2 \text{ ft. per sec. per sec.}}$$

r = distance in ft. of the centre of gravity of the part of the body under consideration from the axis of rotation.

v = rotational speed in ft. per sec. of the centre of gravity of the part.

We will consider a thin, completely round, steel disc which rotates round an axis passing through its geometrical centre, which is at the same time its centre of gravity. The centrifugal forces occurring are equal in every direction so that no disturbing force acts on the disc which could displace it in any other direction. Only internal forces occur and stresses in the material are caused which affect the structure of the disc (Fig. 54). If the rotating disc is supported with two shaft ends during the rotation, except for the frictional resistance of the shaft ends in the bearings, there is only the action of gravity, that is, the weight of the disc in a perpendicular direction on the under part of the bearing. Furthermore, this weight is equally shared between the two bearings so that no sideways force will occur.

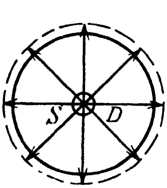


FIG. 54 FORCES ACTING ON A ROTATING DISC WITH ITS CENTRE OF GRAVITY S, COINCIDING WITH ITS AXIS OF ROTATION D

If now an additional weight is placed on the circumference of this disc or, as a result of inequalities in the material, its own weight is unequally distributed, and the disc is set in rotation, the centrifugal forces will no longer be balanced. The centrifugal force will predominate in the direction of the applied weight and have the effect of making a force rotating at the same speed as the disc act on it. When the additional weight is wholly above the centre line during rotation its effect is to lessen the disc weight by its centrifugal force; when it is below, this is increased and there occurs in the bearings an additional pressure of the shaft towards the underside. When the additional weight is at the sides corresponding sideways forces occur (Fig. 55). These forces, changing in direction with the rotation, are the cause of the oscillations or vibrations of rotating machine parts.

The same effect as that which is produced by the additional weight on the disc is also produced when the disc does not run true, that is, when its centre of gravity S does not coincide

with its axis of rotation D, as shown in Fig. 56. This can occur with machines which, when in operation, have the rotor winding displaced to one side or in which the rotor banding -or in

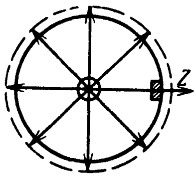


FIG. 55.
FORCES ACTING ON A ROTATING DISC WITH AN ADDITIONAL WEIGHT Z ON ITS CIRCUMFERENCE

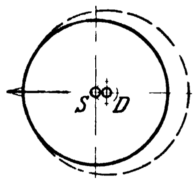


FIG. 56.
DISC NOT RUNNING TRUE DUE TO CENTRE OF GRAVITY S AND AXIS OF ROTATION D NOT COINCIDING.

the case of turbo machines, the rotor end caps becomes loose and causes irregular running. The same effect occurs with commutators which have become unsymmetrical due to unequal wear. With a considerable out-of-balance or very high speed, it may happen that the centrifugal force exceeds the force due to gravity and so much exceeds it that the shaft ends knock against the top half of the bearing.

If two equally large, completely round and equally thick discs having centres of gravity coinciding with the axis of a shaft on which they are placed are set in rotation, the centrifugal forces, just as in the case of a single disc, cancel one another and the combined rotating body will run on its shaft without vibration as in Fig. 57.

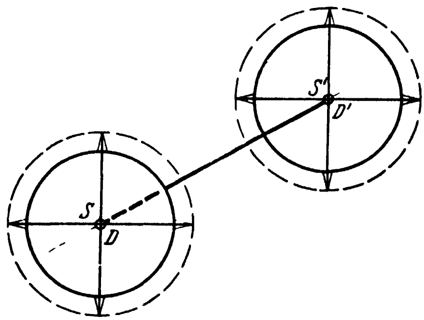


FIG. 57 FORCES ACTING ON TWO DISCS ROTATING ON THE SAME SHAFT
Their centres of gravity S and S' lie in the axis of rotation

If on each disc is now fixed an equally heavy additional weight so that their connecting line A lies exactly parallel with the shaft axis, then during rotation the composite body has a tendency to revolve round the axis of the centres of gravity S,

which is in this case parallel to the axis of rotation and in a fixed relationship to it (Fig. 58). This type of out-of-balance is called an error in *static balance* because the error, as in the case of a single disc, can be determined and cured statically, that is, without continual rotating. (See Chapter VI, para 3.)

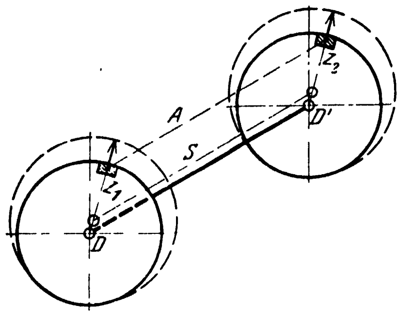


FIG. 58. STATIC OUT-OF-BALANCE CAUSED BY TWO EQUAL ADDITIONAL WEIGHTS Z_1Z_2 ON AN AXIS A PARALLEL WITH THE AXIS OF ROTATION DD'

If the weight on one of the discs is displaced 180° but fixed in the same relation to the axis of rotation, the static effect of the two weights is exerted in opposition, so that the body is still in static equilibrium as regards the axis of rotation. If this body rotates, each disc will endeavour to turn round its own centre of gravity (Fig. 59) which is no longer on the axis of rotation. The line connecting the two weights is now inclined relative to the axis of rotation and, when allowed to turn freely, describes a double cone, as shown in Fig. 59.

If this body runs in two bearings, the vertical or horizontal pressure on the bearings changes with each new position it takes up. At the same time, the pressure on the first bearing increases simultaneously with a decrease in the second one, and vice versa. This variation of pressure in the bearings with rotation causes vibrations and the body is *dynamically unbalanced*. It is called dynamic because it first becomes apparent when the body is maintained in continuous motion.

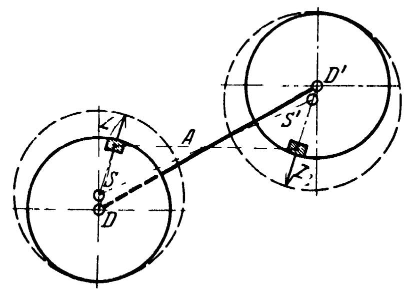


FIG. 59. DYNAMIC OUT-OF-BALANCE CAUSED BY TWO EQUAL ADDITIONAL WEIGHTS IN OPPOSITE POSITIONS ON A STRAIGHT LINE A CUTTING THE AXIS OF ROTATION

The rotor of an electrical machine can be regarded as a

shaft having fixed upon it a series of discs of which each has a fixed balancing error in some direction. It is thus usually a cylindrical body which has a static and a dynamic out-of-

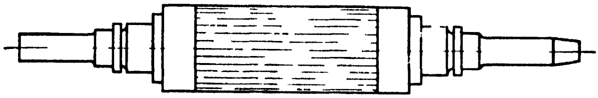


FIG. 60. TWO-POLE TURBO-GENERATOR ROTOR, A TYPE OF ROTOR ON WHICH THE EFFECT OF DYNAMIC OUT-OF-BALANCE IS OF MOST IMPORTANCE

balance. The longer a cylindrical body is, the more disturbance will errors in both static and dynamic balance produce (Fig. 60). With a narrow rotating field as in Fig. 61, the cure of static out-of-balance is of sufficient importance. The effects produced by different balancing errors are also obviously dependent on the speed.

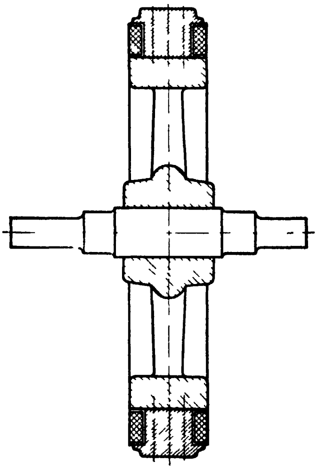


FIG. 61. ROTATING FIELD OF A LOW SPEED ROTOR, A TYPE ON WHICH THE DYNAMIC OUT-OF BALANCE HAS VERY LITTLE EFFECT

2. Causes of Out-of-balance. (*a*) INADEQUATE BALANCING. During the construction of a rotating part of a machine, particularly when this part is not machined all over, unequal distributions of the weight exist as a result of irregularities either in the material or construction, which cause out-of-balance. In order to ensure that such parts shall run without vibration, this unequal weight distribution must be corrected, either by the addition of weights or by the removal of material from the overloaded side, until a precise balance is achieved in that the centre of gravity coincides with the axis of rotation. All rotating parts such as rotors, couplings and pulleys must be balanced. According to the type and speed of the machine parts, they must be either statically or dynamically balanced. Dynamic balancing is particularly necessary for high speed, axially long machines.

Balancing is normally carried out in the factory of the manufacturer, and according to the balancing process used and the degree of precision of the ancillary apparatus, the balance will be either so perfect that the machine runs without vibration, or there will still remain an error and the freedom of the machine from vibration will be improbable.

Most manufacturers of electrical machines possess the necessary equipment, and take particular care to ensure that their product is balanced so that the amount of error is small enough to be negligible and the machine runs without vibration.

During the time a machine is in service, however, new causes of balancing trouble may arise, and the most important of these are described in the following paragraphs.

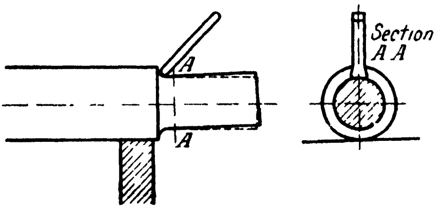


FIG. 62 METHOD OF STRAIGHTENING A SHAFT END

(b) BENT OR UNTRUE SHAFT. When testing for the causes of vibration, one of the first steps is to ensure that the shaft is perfectly true and straight, and that the bearings are properly aligned. It is always necessary to do this before attempting to deal with the actual balancing. Untrue shaft ends must be "trued up" in a lathe. For this purpose, at the outset, a perfectly true portion of the shaft must be fixed in the headstock, and afterwards the shaft ends can be ground or lightly turned to make them perfectly true. For high-speed machines, and turbo-machines, the permissible eccentricity of the shaft ends must not exceed a half-thousandth to one-thousandth of an inch, according to the diameter of the shaft. Bent shafts can be straightened as shown in Fig. 62 by treatment with a specially hardened and shaped tool. Due to the stressing of the layers of the material at the place where it is pressed, the shaft ends can be bent back into the position indicated by the dotted lines. The same effect can also be achieved without the use of such a tool if the shaft is quickly heated to a good heat with an oxy-acetylene flame at the place to be bent. The shaft ends must, in this case, be bent farther than necessary to allow for the cooling which will then bring them back into the required straight line.

(c) DISPLACED WINDINGS. A displacement of the winding

in the case of a high-speed machine having a wound rotor is often first apparent when the machine is put on full load. It produces lack of balance. Winding displacements can only be cured by removal of the rotor banding, re-pressing of the winding and the fitting of a stronger band. If a winding displacement does not become progressively worse, the out-of-balance can be corrected by re-balancing. Loose field-magnet coils of rotating fields are best fixed by driving in wedges of insulation material. How and where this can be done depends entirely on the construction. Subsequent balancing is in any case to be recommended.

(*d*) Loose Rotor Parts. Instances of parts which are not securely fixed, or which become loose on the shaft, such as rotating fields, pulleys, commutator bushes, spiders, etc., seldom occur. Such cases usually become apparent when the machine is operating at low speed, due to knocking or squeaking. Very often these characteristics can only be detected by listening to the bearing with a piece of metal, a key or rod for example, of which one end is held to the bearing and the other to the ear.

If it is feared that a part fixed on the shaft has become loose, but no play can be measured with a micrometer, to pour some paraffin on the suspected part while the rotor is rotating quite slowly will often confirm the existence of the trouble, as paraffin will be squeezed out by air pressure set up. From this it may be concluded that loosening of the parts concerned has taken place, particularly when powdered rust is also forced out, since this is always found if loose parts are rubbing dry against one another. Its occurrence in connection with fixed parts, therefore, always means trouble, and if such trouble is not noticed early the surfaces are in time liable to be completely ruined. Fig. 63 shows a shaft which has become seriously damaged through too loose a fit of the pulley.

Loose parts can be fixed again either by pressing on shrink rings (i.e. over the hubs) or by fixing a clamp screw or by improved keywaying. In some cases it is impossible to avoid removal of the loose parts, bushing them and reassembling either with a smaller bore or larger diameter of the seating. In many cases, electrical welding in bores or on seatings, and the subsequent turning of the welded place, will enable the desired tight fit to be obtained.

3. The Cure of Balancing Troubles. (*a*) Balancing in

SEPARATE BEARINGS. For tracing and curing balancing errors, it is necessary to mount the rotating body so that freedom of movement is possible and so that some device absorbs to a certain extent the forces occurring as a result of the out-of-balance. Rotors, however, are normally so held in their bearings that no very great movement is possible, but the deflection of the rotor shaft caused by the out-of-balance is easily noticeable. For the purpose of this test, the bearings belonging to the machine, or else specially-made balancing bearings, are laid on a foundation which permits a horizontal

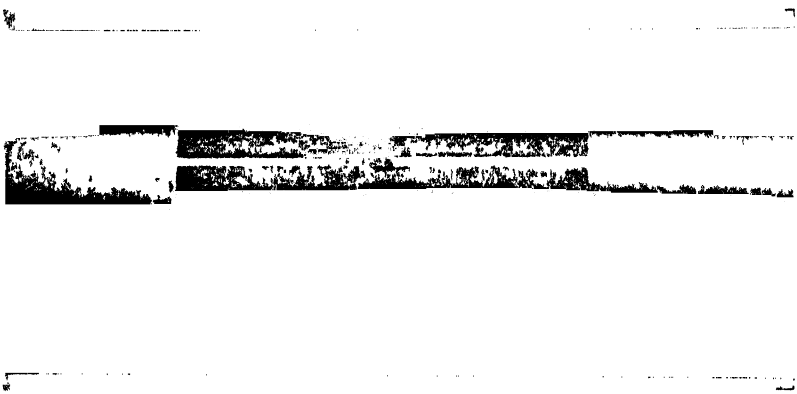


FIG. 63 SHAFT SERIOUSLY DAMAGED BY BADLY FITTING PULLEY

movement of the bearings at right angles to the axis of rotation, and are provided with some form of spring return. The simplest and therefore the most practicable foundation consists of good elastic rubber pads. The spring return is in this case provided by the natural elasticity of the rubber (Fig. 64).

If the machine of which the rotor is to be balanced has plummer block bearings as in Fig. 65, the rubber blocks can be arranged as shown in this illustration. If there are not plummer block bearings, that is, when the machine has end shield bearings, the rotor with special balancing bearings must be set on a hard-wood base. The support should be suitably hollowed out as in Fig. 66 for the reception of grease or oil. With split bearing housings, the under housing alone can be used and is, of course, easily prevented from rotating (Fig. 67).

Since balancing can be carried out at comparatively low

speeds, the lubrication of the shaft ends by means of an oil-can suffices. In this connection, it should be noted that both shaft ends must be equally lubricated, and gravity feed oil lubrication can be used for this purpose.

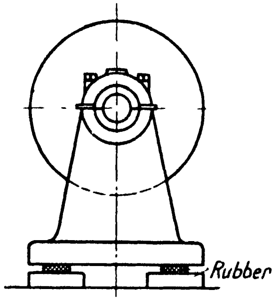


FIG. 64

ARRANGEMENT OF RUBBER PADS FOR BALANCING ROTORS WITH SEPARATE BEARING PEDESTALS

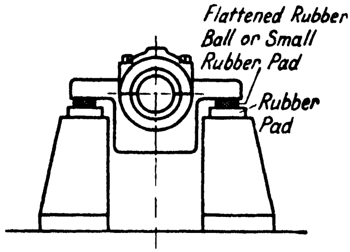


FIG. 65

SIMPLE BALANCING ARRANGEMENT

The simplest method is to drive the rotor with a belt of the same width as, and laid over, the rotor iron. The best type of belt is an endless camel-hair one which can be run slack.

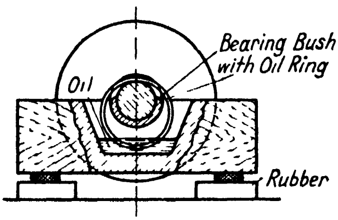


FIG. 66

MOUNTING FOR ROTOR WITH NON-SPLIT BEARING BUSH ON A HARDWOOD BASE

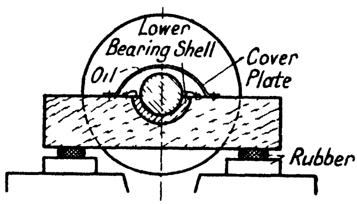


FIG. 67

MOUNTING OF A ROTOR IN ITS LOWER HALF-BEARING SHELL ON A HARDWOOD BASE

Likewise a rotating field can be driven by a belt running on the poles. The driving motor must be reversible. To determine the position and size of the balancing error, the shaft in the neighbourhood of the bearing should be marked on an accurately machined part with a coloured pencil. For this purpose, supports of wood or iron which will hold a pencil and give

marks which are visible are useful. During the starting up or braking of the rotor, the bearing housings must be held fast by wedges. After the attainment of a suitable speed, the belt is loosened and the wedges withdrawn so that the rotor can move freely.

Successful balancing can only be attained when the shaft ends run true and there is no forced movement of the bearing blocks. A shaft or shaft end which is not running true must be straightened or turned before attempting the actual balancing operation. Testing for true running can easily be done with the balancing arrangement described, with steady slow rotation of the rotor and with a perfectly loose and steady belt. The movement of the bearing pedestals or the squeezing out of the oil film between shaft ends and bearings can be visually observed. A spirit level placed on the bearing pedestal will also show any movement of these, caused by the shaft ends being out of truth. This is assuming that the actual error in balance is not particularly large and does not cause the bearing shell to move when the rotation is quite slow.

The ease of movement of the whole arrangement for producing vibrations can be varied at will to suit different conditions by inserting a few rubber plates of different thicknesses and different degrees of elasticity. By pushing the rotor to and fro in the direction of its axis it can be decided if the base is sufficiently elastic.

If the bearing parts are not too firmly wedged and the driving belt is not too tight, as the rotor speed increases, vibrations of greater or less degree will occur at a certain speed according to the magnitude of the balancing error. If the speed is still further increased, the vibrations will also increase in magnitude. If the driving motor is now shut down, the belt loosened and the wedges removed, the rotor can vibrate freely. The vibrations during the running down of the motor will reach their greatest amplitude at a certain speed, known as the *critical speed*. It will be noticed that the nature of the vibrations is such that the rotor with its axis remaining parallel swings to and fro. This oscillation is known as *static critical vibration*.

If the driving speed is raised still further, as in the previous experiment, the rotor will again vibrate at about twice the first critical speed, and the shaft axis describe a "figure of 8" as in Fig. 59. This is *dynamic critical vibration*. Whether the

static or dynamic critical vibration is more marked depends on the magnitude and kind of the balancing error as well as the shape of rotor. To determine the magnitude and position of the out-of-balance and therefore the size and position of the balancing weight to be applied, the method is to allow the rotor to rock backwards and forwards at the critical speed, marking the shaft with a coloured pencil It must be noticed in this connection that the greatest deflection of the shaft as regards both time and position lags behind the point at which the unbalanced force is exerted. The pencil mark is thus always behind the position of the unbalanced weight

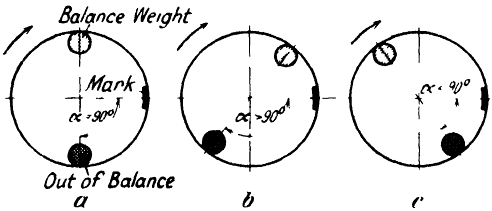


FIG. 68 DETERMINATION OF OUT-OF-BALANCE

(a) Angle α between out of balance and mark with pure static or pure dynamic resonance is exactly 90°
(b) α is greater than 90° at speeds above pure static or dynamic resonance
(c) α is less than 90° at speeds below pure static or dynamic resonance

relative to the direction of rotation, and on this account the proper place for the balancing weight is always behind the pencil mark.

The explanation of this important phenomenon in balancing is that the force acting on the unbalanced rotor as in Fig. 68 (a), (b) and (c) does not, on account of the rotor inertia, move the latter instantaneously. The disturbing force acting as a result of the rotor out-of-balance exerts itself after a certain interval depending on the rotor weight and the elasticity of the foundation. When the rotor has attained its greatest deflection and, at the same time, the pencil has marked the shaft, the position of the unbalanced weight has already turned further round through an angle α, which is dependent on the speed. This angle between the position of the unbalanced weight and the middle of the shaft mark is something between 0° and 180° according to the speed when the mark was made. When working at the critical speed, the marks on the shaft are very short, but either over or under this speed, they are rather longer. This applies equally to the static and dynamic critical speed.

Theoretically, the angle between the unbalanced weight and the mark should be about 90° whether for static or dynamic critical speed, always supposing that the balancing error on the rotor is either purely static or purely dynamic. In practice, the rotor to be balanced has usually both kinds of fault, and the static resonance can be spoilt by the presence of the dynamic balancing error, which has not at that stage been taken into account. For this reason then, even when marking the shaft during the greatest vibrations, the angle α differs appreciably from 90°. This is discussed in more detail below, and illustrated in Fig. 68 (*b*) and (*c*).

The first balancing operation is to cure the static out-of-balance. For this purpose the static resonance is used which appears even with quite a small balancing error. The pencil marks are made on the shaft at each end, or on other parts which are close to the bearings and rotate as nearly true as possible. This should be done for each direction of rotation and using different coloured pencils in each case, e.g. red and blue. The pencils must be firmly fixed on the points of support and during the marking rotated slowly on their axes so that new parts of the lead come into contact with the shaft. The marking must take place as quickly as possible so that the speed does not drop appreciably during the operation. If a hand tachometer is available, the speed at the greatest deflection is measured and noted. When the marking for one direction of rotation has been done, the rotor is brought to rest and set in motion in the opposite direction at the same speed, and when the belt has been loosened, marked with the other coloured pencil somewhat to the side of the first set of marks. If no tachometer is available to control the speed, it is necessary to make a mark at a point of deflection at least as great as any recorded for the other rotation. It may happen that the red and blue marks occur at identical points, as shown in Fig. 69 (*c*). In this case a higher or lower speed must be chosen for the marking so that the marks appear farther apart. When the speed at which static resonance occurs has once been fixed either by marking both shaft ends or by observing the vibrations of the rotor, it is sufficient afterwards to mark only one end of the rotor either at the same speed or at the speed of maximum deflection.

The general rule for curing out-of-balance is to place the balancing weight opposite to a point midway between the

two marks (red and blue) corresponding to the two different directions of rotation. (See Fig. 69 (*a*) and (*b*).)

To cure the static out-of-balance, equal weights must be applied at each end of the rotor as in Fig. 70, if the places where

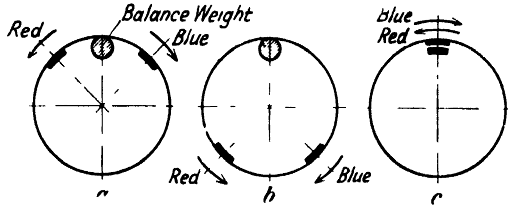


FIG. 69. FIXING THE POSITION FOR THE BALANCING WEIGHT

(*a*) and (*b*) show points midway between the red and blue marks.
(*c*) Case where the position is not defined as marks are too near.

they are fixed are at the same radius from the centre line of the shaft. If, however, they are at different radii, the weights must be chosen in inverse ratio to the radius, that is, the largest

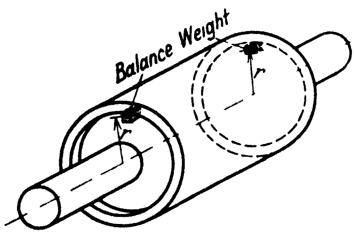


FIG. 70.
STATIC BALANCING BY MEANS OF TWO EQUAL BALANCING WEIGHTS AT THE SAME DISTANCE *r* FROM THE AXIS

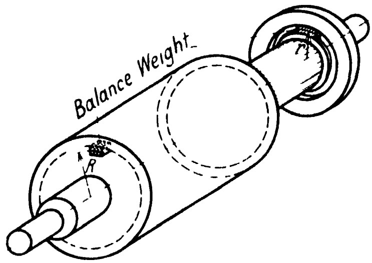


FIG. 71.
STATIC BALANCING BY MEANS OF TWO UNEQUAL BALANCING WEIGHTS PLACED AT DIFFERENT DISTANCES FROM THE AXIS, *R* AND *r*

weight must be on the smallest radius, and vice versa, as in Fig. 71.

The size of the weight has to be determined by repeated experiment, and use made of the fact that the resonance vibrations alter with different weights and that the marks are shorter or longer or show by their change of position an excess balance weight. As long as the marks remain short and appear always on the same place a still larger equalizing weight is necessary, but when the marks are long and change their

position appreciably only a small further correction of the weight should be made.

The correction of the static out-of-balance does not need to be completed before starting the correction for the dynamic balancing error. For this purpose the speed can be raised without danger to twice the static resonance speed. When after this the typical resonance vibrations of a dynamic balancing error occur on the rotor, further pencil marks must be made and the operation repeated for the opposite direction of rotation. The marks will now appear on both ends of the rotor on opposite sides. The dynamic out-of-balance must be removed

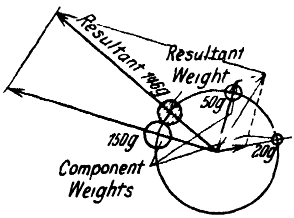


FIG. 72.
GRAPHIC DETERMINATION OF THE VALUE OF A SINGLE BALANCE WEIGHT TO REPLACE SEVERAL SMALLER WEIGHTS ON THE SAME RADIUS

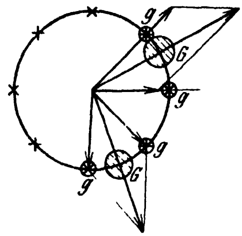


FIG. 73.
GRAPHIC DIVISION OF A LARGE BALANCE WEIGHT G INTO SEVERAL SMALL WEIGHTS g
Places suitable for fixing the small weights.

according to the same rules as the static out-of-balance. In order not to alter the static balancing by the new additional weights, equally large weights, but on opposite sides, must be fastened on each end, assuming that the places where they are fixed are at equal radii. If this is not the case, weights must be chosen inversely proportional to their radii. After the dynamic out-of-balance is corrected as far as possible, a further small correction of the static balance is usually necessary, and finally, an improvement of the dynamic balance.

If, as a result of the balancing, different weights are placed on several places in the same plane with the same relation to the axis, these can be added together geometrically as shown in Fig. 72 by means of the parallelogram of forces. A single large weight which is not easy to fix on the place indicated by the balancing can, by the same method, be replaced by smaller

weights in the same plane and at the same distance from the axis, in positions where they can be more easily fixed (Fig. 73).

Small wheels and discs and also small rotating fields which, to start with, are quite symmetrically machined and made of material as homogeneous as possible can be statically balanced according to a well-known method, in which, as shown in Fig. 74, the shaft ends of equal diameter are placed on exactly horizontal smooth planes and allowed to roll. After a few swings to and fro a position of rest is found at which the heaviest part lies at the bottom, and is duly marked. The disc is now turned round 90° so that the heaviest part lies exactly at the side. In order to test if the place first found is actually the position of the excess weight, the body is once more allowed to roll and it is observed whether it still comes to rest in the same position. If this is the case, it is again turned round 90° and the size of the equalizing weight is approximately estimated by holding the disc with the hand and slightly moving it. The weight of size so estimated is then fixed on the opposite side from the mark, and the whole process repeated until the disc will remain stationary in any position. On account of the friction on the bars on which the shaft is moving, this kind of balancing cannot be so accurate as when the critical speed method is employed.

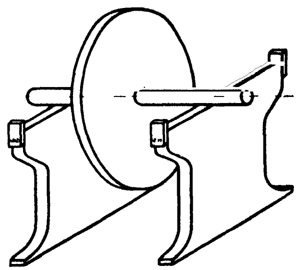


FIG. 74 STATIC BALANCING OF SMALL WHEELS AND DISCS ON HORIZONTAL KNIFE EDGES

Equalizing weights can be of the following kinds and may be fixed in various ways—

Bolted on weights, radially or axially screwed into the rotor.

Ring pieces, fixed in grooves.

Double ring segments dovetailed into grooves and tightened with suitable screws (Fig. 75).

Tin solder laid on the armature or rotor bands, in which case the safe permissible stress on the banding due to the centrifugal force exerted on the solder, must not be exceeded and care must be taken that the thickened part of the banding is not rubbing on the stator winding.

Lead melted and run into specially constructed channels in the rotor.

Spring-rings (Fig. 76); the open part of the ring lying opposite the place where the balancing weight is to be fixed.

The balancing weights must be very firmly fixed; in particular they must be designed for the centrifugal forces. At

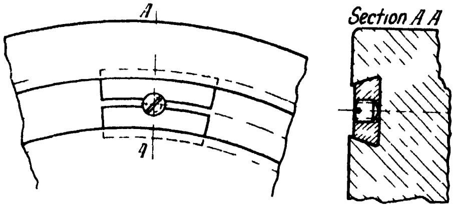


FIG. 75. BALANCE WEIGHT IN THE FORM OF A DOUBLE RING SEGMENT DOVETAILED INTO GROOVES

the same time the weights of the fixing bolts themselves must be included, and it is important to lock these.

The curves in Fig. 77 can be used for the approximate determination of the centrifugal forces which act on the balance weights. The centrifugal forces acting on a fixed balance weight with a given speed and fixed radius of gyration can be taken from it and are stated as a multiple of the applied weight (0 . . . 12 000 times).

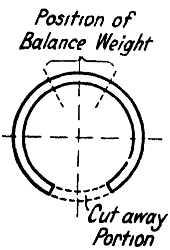


FIG. 76. SPRING RING BALANCE WEIGHT

EXAMPLE. The centrifugal force acts on a weight which is 12 in distant from the axis of rotation at 3 000 r p.m. with 3 150 times the value of the weight. A weight of 0·7 oz. therefore has a centrifugal force acting on it amounting to 0·70 × 3 150 = 2 200 oz, = 140 lb.

For commercial balancing that is, balancing as carried out in motor factories special balancing machines have been developed which, however, are not usually available to the ordinary user of motors. On this account the simplest process and the one requiring the least accessories has been described. It is quite obvious that an experienced workman who is continually occupied on balancing can balance a machine in a shorter time than one only occasionally having to do the job.

An even simpler method of balancing is to balance the rotor in the first place on one side only by clamping the one bearing and only allowing the remaining bearing free play on its

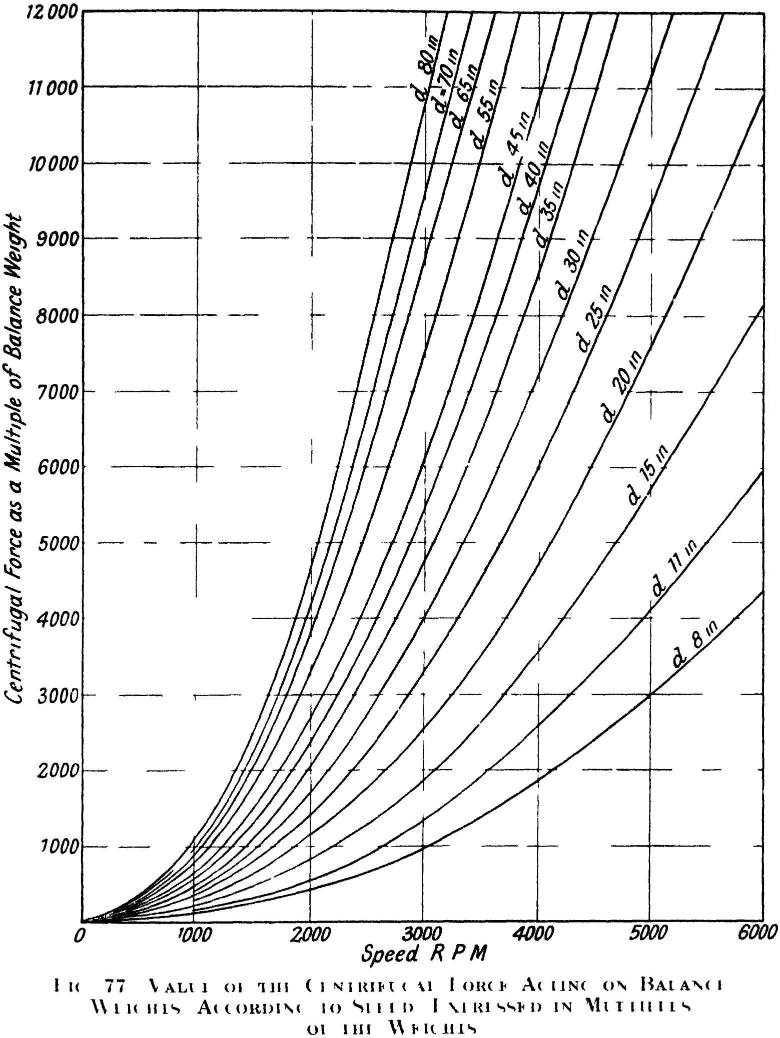


FIG 77 VALUE OF THE CENTRIFUGAL FORCE ACTING ON BALANCE WEIGHTS ACCORDING TO SPEED EXPRESSED IN MULTIPLES OF THE WEIGHTS

(d = diameter of circle in ins lb = lbs balance weight)

elastic base After one end has been balanced in accordance with the rules given here the other bearing is clamped and the previously fixed bearing left free to allow the other end of the rotor to be balanced The accuracy of this method depends on the amount of bearing play For instance when this is large,

a sideways movement of the shaft in the clamped bearing is possible which lessens the accuracy.

(*b*) BALANCING OF MACHINES IN THEIR OWN BEARINGS. This process involves such a large amount of experience and care that it is expedient to call in an expert.

4. Magnetic Out-of-balance. Magnetic out-of-balance rarely occurs without simultaneous winding defects, or with inaccurately centred or out-of-round rotors. The greatest vibrations occur with short circuits in the rotor windings of synchronous machines, whether these are short circuits between single turns of one pole or complete short circuits. Also one part of the rotor winding can be short-circuited by a breakdown to earth in two places. With wrong pole sequence the magnetic lack of symmetry produced will also cause vibrations.

Vibrations from lack of magnetic symmetry can be comparatively easily recognized because they disappear when the current is cut off and reappear if the supply is switched on again. A faulty place can be detected by measuring the resistance of the winding, as already described in Chapter II, para. 6 (*c*). When the pole sequence is wrong, the error cannot be found with direct current, except by the use of a compass needle. If alternating current is used, the voltages between two neighbouring pole pairs should be measured.

On turbo rotors, which are mostly 2-pole, it is necessary to remove the rotor caps and end insulation in order to reach the connection between the pole coils. In many cases, the error can then be found quite easily without measurement by a close inspection of the winding and connections. The correction of the fault can then be done according to its position. If a winding short circuit occurs in rotating fields and turbo rotors at speed, due to the winding or its connections becoming displaced due to the centrifugal force or due to the expansion on account of heating, it is much more difficult to locate the fault. Processes for finding the faulty parts are, in any case, described in Chapter II, para. 6 (*c*).

Vibrations of asynchronous motors as a result of lack of rotor symmetry mostly occur at the slip frequency, and are characterized by an abnormal noise. The causes of these phenomena are more closely described in Chapter XIV, para. 1.

5. Shaft Climbing. High-speed machines can exhibit very marked vibrations if the bearing play, particularly in the upper part of the bearing housing, is too great. A phenomenon then

occurs called *shaft climbing*, in which the shaft mounts up in the oil clearance between the bearing and shaft as a result of the viscosity of the oil, and then falls back again under the influence of the rotor weight. On its return to the original position, the whole process is repeated. The vibrations caused by this may be very violent in bad cases, and have serious consequences. It is noticeable in this connection that the vibration period does not correspond with the speed of the rotor, but is often much smaller. The resonance vibrations occurring with this are dependent on the amount of bearing play, the rotor weight, the balancing error which already exists and the viscosity of the lubricant. Since the latter is dependent on temperature, the oil or bearing temperature is also a factor. If such vibrations disappear with quite a slight change in the bearing temperature, shaft climbing can be definitely assumed to be the cause

To cure shaft climbing, the bearing play in the vertical direction must be reduced to a minimum. This can be done by relining the upper bearing shell and scraping it until the necessary small clearance is achieved. The latter can be best determined by smearing with red lead and scraping the lining off the places at which the shell rests in contact with the shaft.

Another means of reducing the bearing play is merely to file back the bearing surfaces between the upper and lower bearing shells as far as is necessary to give the correct play in the bearing shell. In all cases, however, care should be taken that there is no play between the upper bearing shell and the bearing housing since, in spite of the reduced bearing play, the shaft can still vibrate if it raises the upper bearing shell against the bearing housing.

In many cases, after the upward bearing play has been reduced, the bearing friction and oil temperature are appreciably increased, unless at the same time the sideways bearing clearance is increased to give the shaft free play in this direction, and unless provision is also made for a good flow of oil under the shaft ends.

6. Bedplate Resonance. Sometimes vibrations occur which can be traced back to resonance, for example, when a turbine is mounted on a foundation of which the natural frequency corresponds to the frequency of the small out-of-balance vibrations remaining after balancing. In such a case, the vibration is only very marked at a certain speed, and it is only

troublesome when this speed is the same as the rated speed of the machine. The natural frequency of a foundation can be determined by an experiment in which a smaller machine is placed on it, preferably an easily regulated d.c. motor, which can be run at as large as possible a range of speeds. Its rotor must have been provided beforehand with an artificial out-of-balance by fixing an additional weight. At a certain speed the resonance vibrations of the bedplate will occur and if this speed is the same as the speed of the turbo set, the cause of the vibration of the latter is indicated.

This is best cured either by better balancing of the rotor or by strengthening the bedplate, particularly in the direction of

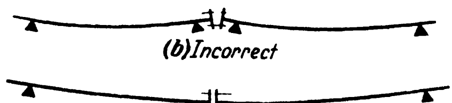


FIG. 78. COUPLING OF TWO SHAFTS

the greatest movement. It is recommended that a vibrometer be used for this work.

7. Faults in Transmission Gear. (*a*) COUPLINGS. In machines which are connected either by rigid or flexible couplings, vibrations may occur if the shafts are not properly aligned. Moreover, the couplings must run perfectly true and not oscillate axially. Each rotor shaft has on account of its own weight a small deflection which must be taken into consideration, particularly with rigid couplings. Coupled machinery will only run smoothly if the shafts are so placed that the faces of the half-couplings have the same clearance between them in the vertical as well as in the horizontal direction, as shown in Fig. 78. It is simple to ensure this by measuring the clearance between the half-couplings with a feeler and adjusting the machines accordingly. The one shaft end must be fixed so that it is exactly in line with the other. This can be tested by laying a spirit level over the edges of the two half-couplings if these have been machined to exactly the same diameter. If this is not the case, however, the concentricity can be adjusted by measuring the play between the half-couplings as explained above.

It is also important that in the case of flexible pin-type

couplings the coupling halves should correspond exactly and that the pitch circles of the holes and of the appropriate pins should have the same diameter so that the pins do not jam in the holes. Owing to the many types of coupling construction now in use, it is not proposed to discuss here the details of further individual types. In general, it is recommended that all couplings, even the so-called "flexible" type, should have the coupling halves as accurately centred as possible and that no undue reliance be placed on the flexibility of the coupling or on the claims made by the manufacturer for it.

The correct centring of couplings and the resultant quiet running of the machine can be spoilt by the heating up of the bearing pedestal of one of the machines by hot oil or by the radiated heat of hotter parts—for example, steam turbine cylinders or steam piping. This may change the relative positions of the shafts of adjacent machines. Since in these cases the heating due to service conditions cannot often be prevented, it must be taken into account at the time of installation. Allowance must be made in the cold condition for the deflection of the shaft which will occur on heating, so that when the machine is hot the shafts are in alignment. The vibrations will then only occur during a short time while the machine is warming up, and will afterwards disappear.

(*b*) Belt, Rope and Chain Drives. Belt and rope drives may cause vibrations if the joints of the belting are bad due to carelessly mounted belt fastenings or to glued joints where the overlapping of the belt ends is wrong relative to the direction of rotation of the pulley, or again, if the spliced joints of woven belts or ropes are badly made. The contact between such bad joints and the driving pulley causes a series of impacts. Belts running with a sideways pull induce axial movement, varying in direction, of rotors, which in turn knock against the bearing shoulders and thus cause vibration.

With chain drives the principal causes of trouble are inadequate support of the chain sprockets as well as defects in the engaging of the sprocket and chain, which may lead to vibration either of the driving or the driven machine.

Practical rules are given in textbooks on the subject, regarding the best pulley diameters and distances, as well as belt and rope dimensions. Belts and ropes working with their driving pulleys under proper conditions ought not to produce appreciable vibration.

(c) Gear Drives. When gear drive is employed for electrical machines, hammering may occur due to careless installation predisposing the driving and driven machines to vibrations. The rather inaccurate and carelessly machined gear drives which are common in the paper, cement, textile, and iron industries are particularly subject to such troubles. The faults most likely to occur on these drives are inaccurate tooth pitch, lack of machining of the teeth or careless machining; inaccurate engaging of the teeth or too much tooth wear resulting in too great play between them: out-of-round gear wheels: axes not parallel in spur gearing; wrong angle in the case of bevel gearing; too great axial play, especially in the case of bevel and helical gearing; inaccurate balancing of the gear wheels.

CHAPTER VII

BEARING TROUBLES

1. Overheating. The permissible temperature rise of bearings according to British Standard Specifications is 45° C. That is to say, with an ambient temperature of 35° C., the highest permissible temperature for the bearing is 80° C., the temperature being measured in the most accessible portion of the bearing. Bearings can, however, operate successfully at higher temperatures if the lubricant is suitable. Occasionally, two bearings having exactly the same construction and loading will exhibit an appreciable difference in temperature. This may be because the cooler bearing is near a coupling or a cooling air duct and is consequently better cooled than the other.

According to the construction and lubrication overheating of bearings may be caused by deficiency of oil or cooling water, unsuitable lubricant, too little bearing clearance, loss of oil between bearing and shaft, too great bearing pressure, unsuitable bearing material, rough shaft, or rubbing of the shaft on the bearing caps.

In the case of ring lubricated bearings, the oil supply can be interfered with by the ring sticking, or too slow rotation of the ring due to dirty or thickened oil caused by foreign matter such as sawdust, flour, cotton fibres, dust, etc. Jamming of the ring in the groove and magnetic influences on iron rings are also causes of trouble. Bearings fed by pumps or gravity oil systems may have obstructed channels. When oil is circulated by a pump, the quantity supplied may be too small because the oil is too low in the oil tank and the opening of the oil pipe only partially submerged, so that air is drawn in. This can be diagnosed from the milky appearance of the oil.

Insufficiency of cooling water is chiefly caused by the breaking down of auxiliary pumps or by obstruction of filters in the supply system as well as the calcination or fouling of coolers. Depending on the losses to be conducted away, insufficiency of cooling water is usually not apparent for some time, when a slow but steady increase in bearing temperature is observed. When bearings having water coolers which are adequately

supplied with cooling water still exhibit a steady temperature rise over a period of weeks or months, this usually indicates calcination or fouling of the cooling tubes, as explained in Chapter XXXVII, para. 6. Many bearings having additional water cooling can remain in service for a long time without water and not exceed the temperature limit.

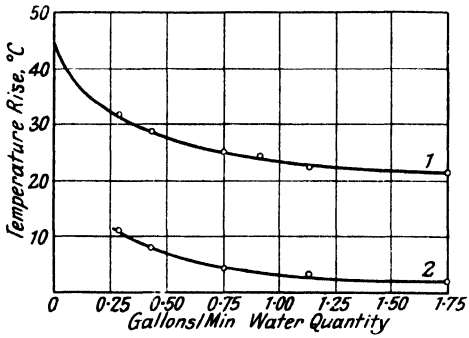


FIG. 79. INFLUENCE OF THE COOLING WATER QUANTITY ON THE BEARING TEMPERATURE OF A MOTOR AT 3 000 R.P.M., AND 500 kW. RATED OUTPUT

(1) Heating of bearing oil with ambient temperature of 30° C.
(2) Rise in temperature of cooling water.

The amount of cooling water necessary for water-cooled bearings may be calculated from the formula—

$$Q = (3{\cdot}14 \times P)/\Delta\tau\text{; where}$$

P = Loss in bearing in kW.

Q = Cooling water supply in gal. per min.

$\Delta\tau$ = Temperature rise in cooling water in ° C.

From this we have for 1 kW. loss and 1° C. temperature rise, about 3·3 gal. per min., so that for the usual temperature rise of about 10° C., 0·33 gal. per min. per kW. will be necessary. The bearing loss is approximately

$$P = \frac{2 \times F \times v}{10^5}\ \text{kW. in which}$$

F = Projected surface of the bearing in in.^{2}

= journal length × diameter.

v = Journal speed in ft. per min.

From this we have for 10° C. temperature increase a cooling water quantity of

$$Q = \frac{0{\cdot}65 \times F \times v}{10^5} \text{ gal. per min.}$$

As the cooling water supply is increased, the heating of a bearing first falls rapidly and then less so, as in Fig. 79. After

FIG. 80. COOLING WATER TUBE OF A BEARING SHELL DAMAGED BY CORROSION AFTER THIRTEEN YEARS' SERVICE

the temperature of such bearings has reached a certain level it will not show any further decrease, however much the water quantity is increased, since with a given cooling surface the heat transfer due to increased speed of flow of the cooling water is not further improved.

The cooling water may leak into the oil in some cooling systems due to the connections and junctions not being watertight, or as a result of mechanical damage or corrosion of the cooling tubes (Fig. 80). Traces of moisture in the lubricant are not particularly dangerous, but larger quantities of free water,

which spoil the lubricating effect by destroying the oil film, are a serious matter since overheating, and in bad cases collapse of the bearing, will result.

To-day no difficulty is experienced in finding a suitable lubricating medium, but the recommendations of the machine supplier should always be taken into account. A word of warning must be given respecting so-called "super-lubricants" which are claimed to be exceptionally effective in service. While, with a good lubricant, the running surfaces of the bearing are smooth and polished, with these special lubricants they may become resinous and sticky and thus increase the losses.

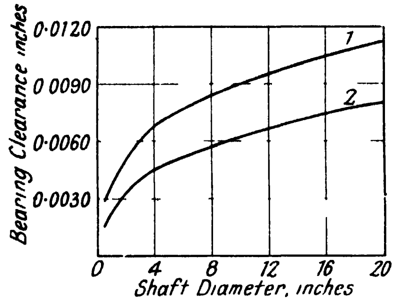


Fig. 81 Bearing Clearance Relative to Shaft Diameter

(1) For easy bearing fit
(2) For closer bearing fit

The curves give the average of the maximum and minimum figures (German standards)

Friction and consequent heating may sometimes be experienced with ball and roller bearings as a result of too much or unsuitable grease. This should not arise if the recommendations of the machine supplier and of the bearing maker are observed. All lubricating media should be free from foreign matter such as dust, sand or metallic chippings, which damage the bearing and cause excessive wear on its surfaces. On this account a thorough cleaning of the housing and a renewal of the grease is absolutely necessary after any bearing failure. Chapter XXXVIII, para. 1, contains further information on lubricants.

Excessive heating also arises from too small bearing clearance. This may be due to the type of bearing, the journal speed, and the type of machine. (See Fig. 81.) An easy medium clearance is best for slow-running machines with horizontal shafts, and a slacker clearance for those at higher speed. When determining the correct bearing clearance for asynchronous motors, it is necessary to pay special attention to the size of air gap.

The oil should flow freely along the oil grooves between the shaft and bearing, and on this account the oil grooves should be well rounded. Sharp angles as shown in Fig. 82 (a) scrape

the oil off the shaft, and prevent the formation of a proper oil film. The heating of the bearing can very frequently be reduced solely by improvement of the shaping as in Fig 82 (*b*).

Too much radial bearing pressure can be brought about by excessively tight belts, ropes, or chains, and also by using a pulley of too small diameter. Excessive pressure in the axial direction, that is, on the bearing shoulders, either steady or consisting of a series of impacts, may be caused by too great magnetic pull, if the rotor is too much displaced in the stator; by couplings producing an axial thrust: by driving machines; by direct-coupled pumps and fans or by expansion of the shaft due to heat combined with insufficient axial clearance. A continuous excessive axial pressure overheats the bearing and leads to wear of the thrust shoulder. On the other hand, axial blows of brief duration only hammer the bearing shoulder without causing heating. These may be due to belts with sideways pull, bad gear wheel alignment, insufficiently balanced rotor, or irregularities on the bearing shoulder.

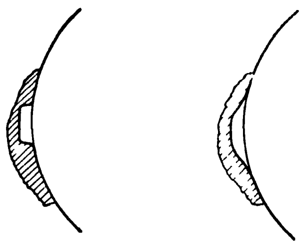


FIG. 82.
SECTIONS OF OIL GROOVES

To determine the cause of excessive axial thrust, the machine should be first run uncoupled and tested to see if the thrust is still excessive and if there is sufficient axial play. In the case of a one-sided magnetic pull the stator can be displaced relative to the rotor, or under some circumstances the shafts or bearing shoulders can be machined back. The stator or rotor laminations must on no account be forced axially due to the danger to the windings.

Bad manufacture of the bearing lining resulting in the inclusion of slag, sand, cement, and ash may increase the friction and heating to an abnormal extent, or cause grooving of the shaft. Further notes on bearing materials are given in Chapter XXXVII, para. 3.

A rough shaft surface or a shaft damaged by careless handling during installation may also increase the heating, as well as skewed bearing caps, oil guides and washers, or rubbing of the cast-iron bearing lips on the shaft. Such troubles mostly occur when the shaft sinks as a result of bearing

wear. Bent shaft ends will also jam in the bearing and cause overheating.

If the troubles described here are not noticed at an early stage, a breakdown of the bearing will probably result, and if the bearings are of white metal they will melt, and in some instances the rotor may be damaged. Bronze bearings tend to seize fast to the shaft so that they can often only be separated from it by heating or by light hammering.

Repairs on shafts and bearings must always be carried out with great care. Rough shaft ends must be ground clean, bent ends made straight and polished, and the bearing scraped to the appropriate fit after the shaft is ground.

2. Bearing Currents. Bearing shells and shafts may also be pitted by currents flowing through the bearing, which may occur in various ways. Lack of symmetry in the iron or in the winding can cause a magnetic flux which no longer takes the proper path through the pole and armature, but remains in the armature and flows concentrically in planes normal to the shaft. Short circuits also, especially when single-phase, give rise to this lack of magnetic symmetry and a voltage is therefore induced in the conducting circuit formed of shaft, bearing, housing, and bedplate. In some circumstances, it may break down the insulating oil film of the bearing and a so-called *bearing current* flows through the circuit described which, if of sufficient magnitude and duration, damages the bearing. Occasionally, the passage of sparks to the bearing housing lips will be noticed. To prevent bearing currents, bearing pedestals are often insulated from the bedplate. It is necessary, however, to take care that this insulation is not bridged over by a metallic conductor such as a water pipe, or the wire armouring or conduit of auxiliary circuits. If signs of bearing currents are apparent, such as fine points of roughness on the bearing lining and shaft, the state of this insulation should be tested.

In addition to the bearing currents mentioned above, bearings may also carry current if a considerable earth exists outside the machine in the armature circuit of generators and motors, and at the same time a second breakdown to earth occurs inside the armature. The short-circuit current then flows through the bearing and brings about the results mentioned. Fig. 83 shows portions of the shaft and bearing shell of a d.c. machine which was damaged in the way described.

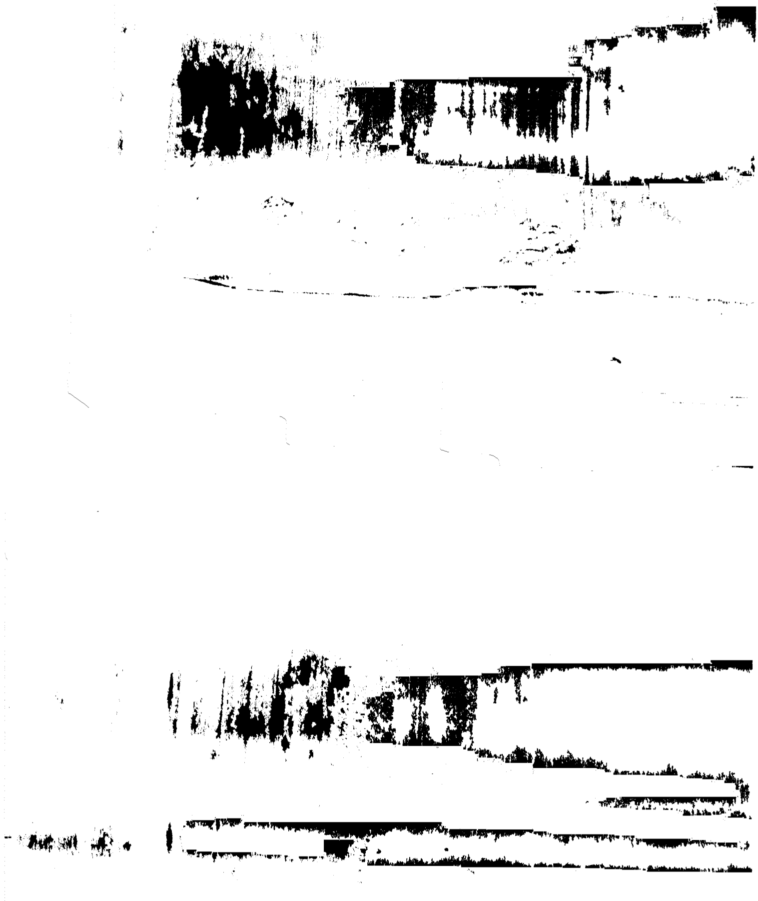


FIG 83 SHAFT AND BEARING SHELL DAMAGED BY BEARING CURRENTS

3. Oil Throwing. One of the chief causes of oil throwing is the use of too much oil. In many factories the maintenance staff are under the impression that the machine bearings must be inspected and refilled daily, and the oil chambers are often

so overfilled that the oil creeps along the shaft. All bearings have either oil level gauges or indicators which should always be used for determining the proper level when filling with oil.

Besides these chief causes, damaged cover plates and bearing caps allow the oil to creep along the shaft. Open bearing housings allow the escape of oil vapour. In addition, the windage produced by couplings may suck oil out of the bearing. In dirty positions insufficient protection allows the collection of dust on the bearings along which oil may creep.

Oil throwing is particularly harmful when it affects windings, slip-rings, and commutators. The oil mixed with dust often forms a thick dirty layer which may damage the varnish on the windings.

Naturally, if oil is lost continuously, the bearing housing is soon emptied and the bearing damaged from sheer lack of oil.

4. Renewal of the Oil. When machines which have been standing are replaced in service, the bearing oil should be renewed to start with, especially if the old oil appears black and muddy. After bearing and shaft are polished and run in, complete replacement of the oil again is very seldom necessary —probably not more than once a year. In this process the bearing should be washed out with petrol before the new oil is put in. In general, it is to be recommended that the bearings of electrical machines should not be continually filled up with oil from a can unless there are specially severe operating conditions. The bearing cover should remain closed—a good bearing will operate many months without attention.

CHAPTER VIII

FAILURES TO GENERATE AT NO-LOAD

1. D.C. Generator Gives No Voltage. (*a*) EXCITER CIRCUIT IS BROKEN OR HAS ABNORMAL RESISTANCE. If d.c. generators fail to excite they should first be tested for breaks and bad contacts in the field circuit. These may occur in the field coils or the coil cross-connections due to breaking of a wire, or insufficiently secure terminals, or in the shunt regulator as the result of broken wires or loose contacts. Often corrosion of the contacts is sufficient to raise the contact resistance so that self-excitation is impossible.

If, however, the generator excites initially but at a certain position of the shunt regulator the voltage is lost, it may be that in the regulator position under consideration a few contacts stand back and the sliding contact cannot touch them. Loose contacts may also be the cause.

A testing lamp or an insulation test box should be used when testing for a break in the circuit. These are available to-day in almost every workshop, and a large fault can easily be found with them. If the trouble is only a bad contact, this is not so easily located, even with both appliances. With the usual large supply voltages, the increase in contact drop is of no importance, but it may affect the excitation in the case of the small residual voltages of machines. In such cases the situation of the fault is best found by disconnecting and examining the most accessible contacts. Repairs not carried out in a workmanlike way on field coils or their connections can cause bad contacts due to varnish having accumulated on the wrong parts, or to careless soldering.

(*b*) REVERSED FIELD WINDING OR REVERSED COILS. When the field winding of a self-excited d.c. generator is reversed, the armature voltage induced by the residual field sends a current in such a direction through the field winding that the residual field is weakened and the self-excitation opposed. If a voltmeter with a small measuring range is connected between the armature terminals of a self-excited d.c. machine, with an otherwise open-circuited armature, and the connection of the whole field winding is reversed, the gradual sinking of the

residual voltage can be observed if the field regulating resistance is slowly switched out. Reversed connection of the field winding of a separately excited d.c. generator does not stop the excitation but alters the polarity of the generator.

The "reverse connection" of a field winding in which single coils only are reversed usually results in failure of the generator to excite. The influence of single reverse connected poles and the testing for correct pole sequence is described in para. 3 (*c*).

(*c*) FIELD REGULATOR IS REVERSE-CONNECTED. Most field regulators have three connecting terminals, as in Fig. 84. When the generator is connected wrongly, for example, on to terminals 1 and 3 instead of 1 and 2 it usually will not excite.

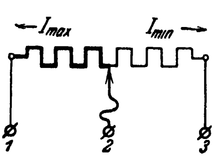


FIG. 84. CONNECTION DIAGRAM OF A FIELD REGULATOR

It may be that the field regulator is wrongly connected to terminals 2 and 3 and its operation is reversed. Those resistance steps which carry the least current and have the greatest resistance are switched out at the end instead of at the start of the regulating process. The regulation in this case is insufficient and the regulator may become too hot.

(*d*) COMMUTATOR CONTACT RESISTANCE IS TOO GREAT. An important cause of the non-excitation of a self-excited d.c. generator is that the contact resistance of the commutator may be too great. This difficulty occurs mainly on low voltage machines. It arises with a dirty or oxidized commutator, insufficient brush pressure, unsuitable grade of brush, or as a result of marked chattering of the brushes, possibly caused by high segments or high mica, or by an out-of-round commutator. It will often be found sufficient to increase the brush pressure, so as to reduce the resistance to establish the self excitation.

Dirty and oxidized commutators should be cleaned with the brushes raised by fine grained carborundum cloth, pumice stone, or other suitable abrasive material.

The choice of brush grade and brush pressure is discussed in more detail in Chapter V, para. 5. The overhaul of commutators is described in Chapter V, para. 12.

(*e*) COMMUTATOR SEGMENTS ARE SHORT-CIRCUITED. With low voltage d.c. generators such as are used for electrolytic purposes and as exciters for synchronous induction motors, metallic brushes are frequently used. If the grade of these is

wrongly chosen, it may happen that the slots between the segments become full of metallic dust, which finally prevents the self-excitation of the generator. Contamination by oil can also lead to short-circuited segments. To cure this, apart from using the proper grade of brush, the slots between the segments must be carefully cleaned out.

(*f*) Brush Position is Wrong. The non-excitation of a d.c. generator may be due to wrong brush placing. It sometimes happens that after overhaul of the machine the brush holder is replaced reversed, so that the brushes are very far out of the neutral zone although the brush rocker is apparently resting on the right marks.

In modern generators the operating position of the brushes is always indicated by a mark on the brush rocker, and in interpole machines the brush position does not change between no load and full load. If there is no mark on the brush rocker the proper position can be determined for most types of armature winding because the brushes are placed opposite the centre of the main poles. Some manufacturers also mark one particular slot, and the conductor to the commutator belonging to it, with a coloured mark. The neutral zone can be approximately found with the help of such a mark by turning the marked slot under the centre of an interpole when the brush should rest on the segments marked as belonging to it. When the brushes are placed as indicated by this procedure, the generator should excite. To ensure good commutation, however, the brush placing must be more accurately fixed as explained in Chapter V, para. 6 (*e*).

It should be mentioned that a small displacement of the brush rocker out of the neutral zone opposite to the direction of rotation improves the self-excitation.

(*g*) Direction of Rotation is Reversed. In the case of a self-excited d.c. generator the direction of rotation may be wrong relative to the connections of the field winding. The cure for this is to reverse either the connections of the field winding or the direction of rotation. Wrong direction of rotation of a separately excited d.c. generator only reverses the polarity.

(*h*) Residual Magnetism is Lost. If the residual magnetism disappears there will be no self-excitation of the generator. Generators that have lost their residual magnetism must be properly excited again from an external current source. Generally speaking, only a few cells of an accumulator battery are

necessary to excite the machine externally sufficiently strongly to restore the self-excitation. In this process both leads to the field winding must be separated from the machine terminals, and at normal speed of the machine the field winding only should be separately excited. The separate excitation of the machine is maintained for a few minutes and then its normal connection restored. If the generator has to be connected in parallel with other generators, the polarity must be checked to ensure that it is correct.

(*i*) ARMATURE WINDING IS OPEN-CIRCUITED OR SHORT-CIRCUITED, OR IS WRONGLY CONNECTED. When there is a break in the armature of a self-excited generator it will usually not produce a voltage. If the generator is tested by being driven with separate excitation, violent sparking occurs when there is actually a break in the armature circuit, and the segments between which the break occurs soon become black and burnt. If there is in the armature winding a short circuit caused by the direct metallic connection of adjacent turns of one coil, the self-excitation again may be prevented. If the generator is separately excited, sparking, blackening of the segments concerned and eventually overheating of the faulty part of the winding occur.

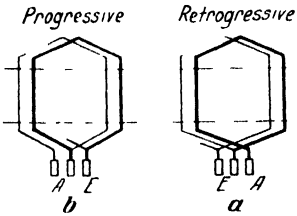


FIG. 85. PROGRESSIVE AND RETROGRESSIVE ARMATURE WINDINGS

Apart from these it has more than once been found that a d.c. generator would not excite after the installation of a spare armature. The cause was that the coils in the spare armature were not wound in the same way as in the original armature. For example, a retrogressive winding might have been used in the new armature while the old one had a progressive winding—see Fig. 85. To cure this, it is necessary to change over the connections of the field winding.

The same fault may also occur when an armature is rewound. It can, however, only arise in connection with wire windings since with bar windings, conductors of the correct shape and length are usually prepared before being placed in the slots.

(*k*) ARMATURE CIRCUIT IS SHORT-CIRCUITED EXTERNALLY. A short-circuited self-excited shunt connected generator will produce no voltage. On the other hand, if the brushes are

displaced backwards a false self-excitation can occur on account of the compounding effect of the armature reaction field. Under these circumstances, the current in the short-circuited loop is many times the rated current, the commutator sparks, and the generator continues to generate even with the field winding broken. This can only be cured by stopping the generator quickly or by opening the circuit by a switch having overload trips.

(*l*) Shunt Field Windings Broken Down to Earth or to the Main Circuit. Breakdown of the field winding to the iron does not affect the running of a generator as long as there is not a second breakdown. Non-excitation, however, is possible as soon as the field winding has two earths, so that a large portion of the winding is short-circuited. In installations having an earthed conductor, the earth connection forms the second earth as in Fig. 86. According to the position of the earth and its contact resistance, its effect varies, and under some conditions a short-circuit can also be produced. Earths generally occur on the field coil cross-connections, and with careless insulation of the field coils, short-circuiting due to pressure at the pole corners may occur. As a result of the short circuit between layers, and with progressive burning of the insulation in the neighbourhood, the insulation between the coil and the iron may also be burnt and finally cause a breakdown to earth.

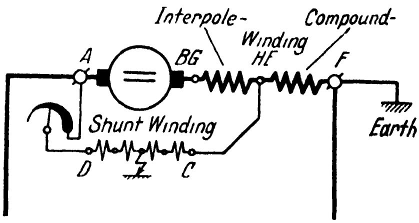


Fig. 86 Breakdown to Earth in the Field Winding.

Breakdowns to other windings through which the main current flows, whether the compound winding or the interpole winding, may have different results according to their position. In Fig. 87 a few cases are shown diagrammatically. A short-circuit at *a* will partly or wholly short-circuit the shunt winding, according to the position of the parts which are short-circuited, due to the very small resistance of the interpole coils. If the contact comes at *b* the excitation is not affected, but the diverting of the interpole winding will result in bad commutation. A connection at *c* will operate the same as one at *a* and short-circuit the shunt field winding. Connection at *d* causes

shunting of the compound winding and consequently diminishing of its effect. A connection at *e* due to wrongly connected leads results in over-excitation of the machine due to the short-circuiting of the shunt regulator. Short-circuited parts of a field winding remain cold; therefore when very different degrees of heating are exhibited by individual poles of a field winding, the coil remaining cool should always be tested first.

A measurement of the voltages on the single poles will also indicate the faulty parts. Earths can be detected under service conditions by measuring the voltage between the machine terminals and the earth. If on one terminal there is no voltage or little voltage, but the other terminal has the full machine voltage to earth, this suggests a breakdown of those poles giving no voltage to earth. Alternatively, the machine can be tested at standstill with an insulation tester. Breakdowns to earth should be investigated as set out in Chapter II, para. 4.

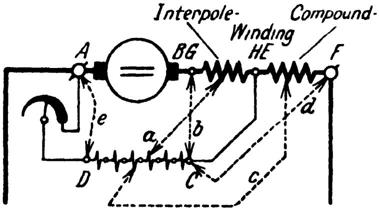


FIG. 87. SHORT CIRCUITS BETWEEN FIELD WINDING AND MAIN CURRENT WINDING

(*m*) SWITCHGEAR FAULTS. Failure of the machine voltage can frequently be traced to defects in the instruments and switches associated with them, or to meter shunts or external resistances. When such troubles occur, therefore, the first thing is to ascertain whether or not the instruments and their leads are in order.

2. A.C. Generator gives No Voltage. (*a*) DEFECTS IN THE EXCITER. In by far the majority of cases, the cause for the failure of an a.c. generator to produce a voltage is to be found in the exciter, and the usual fault in the exciter is a dirty commutator. The most common causes of lack of voltage in d.c. generators, which are described in Chapter VIII, para. 1, may be taken to apply to exciters.

(*b*) ROTATING FIELD CIRCUIT IS BROKEN. A break in the rotating field circuit or in the main current circuit of the exciter may arise as the result of a broken or loosely soldered connection. In addition, brushes may no longer ride properly on the slip-rings or on the exciter commutator. On account of wear, they may be wedged in the brush boxes, or stick in the holders owing to the presence of dust.

(*c*) Field Circuit is Wrongly Connected. The voltage can only be entirely lost when all the poles are either north or south, because the field winding is wrongly connected. This fault may occur after field coils have been completely dismantled for overhaul, and afterwards either not replaced correctly, or wrongly connected. It can be assumed that this is the cause of the trouble when no voltage can be detected on the stator terminals, although there is full voltage and current in the field circuit and the stator winding of the generator is in order. The method of determining the proper pole sequence is described in Chapter VIII, para. 3 (*c*).

(*d*) Earths and Short Circuits in the Field System. If by chance two breakdowns to earth occur simultaneously so that the main current of the exciter flows through these earths and does not flow through the field winding, the generator cannot produce a voltage. The same thing happens if the leads to and from the field winding are touching on opposite sides. The insulation of the leads may be damaged by clamp screws, or the insulation on a connecting bolt to a slip-ring may have been damaged where it passes through a ring. In the troubles mentioned, it is characteristic that since the exciter in the field circuit is almost short-circuited the rated current occurs at much below the normal excitation voltage.

(*e*) Stator Winding is Open-circuited or Reverse-connected. A break in the stator winding can be detected either by running the generator at no-load and measuring the voltage or, when the machine is at standstill, by measuring the resistance. When one conductor of a star-connected three-phase generator is broken, a voltage can only be measured on two terminals, but measurement of the voltage on a delta-connected winding gives approximately equal voltages between all three terminals. If the phase connections lie outside the machine, the faulty lead can be easily detected by separating the leads. If the phase leads cannot be separated, resistance measurement must be used for the purpose. In this case twice as large a resistance is measured between the two terminals of the faulty phase as between the remaining terminals. If one phase consists of two or more parallel winding circuits and only one circuit is broken, the ratios between the resistances stated no longer hold good, but in this case the generator gives at no-load the same voltages between all terminals.

The reverse connection of the stator winding can only cause

lack of voltage if, by chance, two equal parallel circuits of one phase are so connected that they have the effect of cancelling one another. This trouble could, however, only occur after altering or rewinding the stator.

3. D.C. Generator gives Too Low Voltage at No-load. (*a*) SPEED IS TOO LOW. This fault usually occurs in small plants having only one generating set, and the driving machine is often the cause. The water quantity, the head of water, or the steam pressure can be too low, or defects in the governor gear may prevent proper speed control. In addition, too great slip of the driving belt or rope, or slipping of the centrifugal couplings, can all lower the speed.

The usual apparatus nowadays for measuring the speed is the hand tachometer, but speeds up to about 150 r.p.m. can be determined by inspection with the aid of a mark on the rotating body. In a.c. generators, the speed can also be observed by a frequency meter. The change of the voltage will be greater or smaller according to whether a machine is self-excited or separately excited, and whether the exciter is also affected by the speed variation.

(*b*) EXCITER CIRCUIT HAS EXCESSIVE RESISTANCE. D.c. machines of low voltage, for example, machines for electro-chemical works and exciters for synchronous induction motors, may fail to attain full voltage if the connections between machine and field regulator are too long, or of insufficient section. It is advisable in these cases to place the field regulators as near the machines as possible and always to dimension the connecting leads generously with a view to a small voltage drop. It is also obvious that excessive resistance may occur due to dirty contacts, or in the field regulator itself.

(*c*) EXCITER WINDING IS REVERSED—CHECKING POLE SEQUENCE. The greater the number of physical poles wrongly connected or short-circuited, and the smaller the number of magnetic poles in the machine, the more obvious is this trouble. It may be that wrong connections have been made after repair of the field windings. Either connections are reversed by mistake or the pole coils are replaced so that left-hand and right-hand coils are changed over. Fig. 88 gives no-load voltage curves taken on a d.c. shunt generator of 82 kW. and 550 volts to demonstrate the effect of the error when one or two poles are wrongly connected. With two wrongly-connected poles, the machine scarcely produces any voltage. The cutting

out of whole pole coils by short-circuiting is a less common trouble. It can occur where the coil leads from the inside layer short with the outer layers of a field coil; also with short circuits between pole connections crossing one another, or due to earths on two different poles. In Fig. 88 are shown

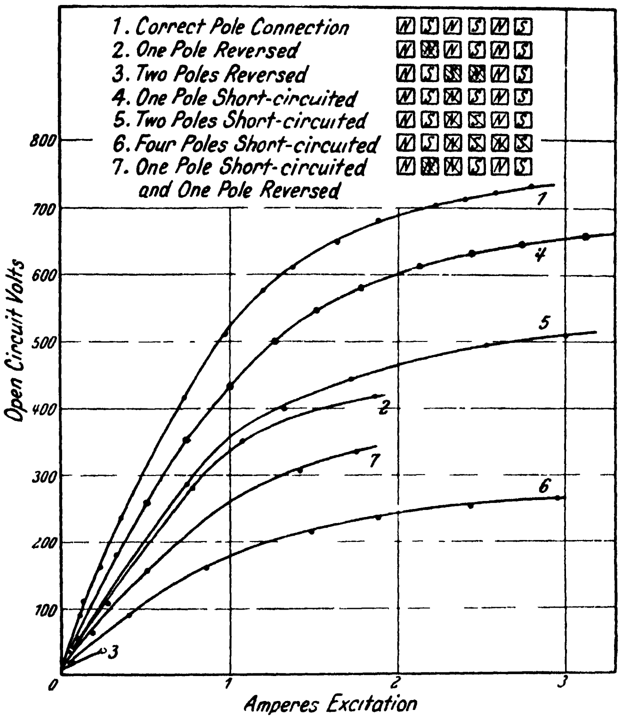


FIG. 88. EFFECT OF REVERSED OR SHORT-CIRCUITED POLE WINDINGS ON THE NO-LOAD VOLTAGE OF A SELF EXCITED D C SHUNT WOUND GENERATOR FOR 82 kW. 550 VOLTS, 6 POLES

also the voltage curves of the same machine when one or more poles are short-circuited.

When field windings are connected in two parallel circuits, a connection perhaps introduced when the machines were modified for a different voltage, the parallel branches may, after an overhaul, be connected in series as at first. The windings then have a decreased excitation effect.

When all poles of the field winding are connected in parallel,

a very rare construction, one pole alone may be inefficient due to a break in its leads or in the pole coil. This actually produces the same effect as the short-circuiting of a pole when all coils are series connected.

When complete pole coils consist of sectionalized coils, there is the possibility that some of these may be reverse connected, causing an appreciable weakening of the poles concerned.

Apart from its effect on the voltage, reversal or short circuit of the pole coils in d.c. machines with lap or multiple circuit windings has a bad effect on the commutation. Heavy equalizing currents, sparking and increased heating of the armature winding and of the commutator occur. The operation of machines having wave wound armatures is, however, only comparatively slightly affected.

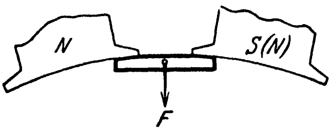


FIG. 89.
TESTING THE CORRECT POLE SEQUENCE BY THE MAGNETIC PULL

To check the pole sequence the polarity of the individual poles can be tested with a compass needle. South and north poles always should lie alternately.

Another process consists in separately exciting the field, and with an iron bar testing the magnetic pull as in Fig. 89. If two like poles are adjacent, or if one pole is short-circuited, the attraction on the iron is much less than if the pole sequence is correct. The force can either be measured or estimated by the hand in pulling the piece of iron away. For proper coil connection with similarly wound coils, adjacent coils should be connected so that finishing lead is to finishing lead and start lead to start lead.

(*d*) FIELD WINDING HAS SHORT CIRCUITS BETWEEN TURNS OR LAYERS. These short circuits may sometimes cause decreased voltage. They must, however, cut out quite a large part of the windings before they are noticeable. Having regard to the large number of turns of the field windings of d.c. machines, it is very unlikely that shorts between adjacent turns or layers will appreciably reduce the voltage.

In order to find the faulty pole the resistances of single coils must be measured. With direct current measurement, only the larger defects are detectable, since the difference of the resistances of individual poles can often be relatively large when compared with the resistance of a few short-circuited

turns. The resistances of individual poles measured with direct current may vary ± 2 per cent from the average value. It is better to carry out this test with alternating current. Short circuits of even single turns are quite noticeable due to the considerable differences of the impedance and the excessive heating of the affected part In addition, wrongly connected poles or wrongly connected coil parts are more easily detected with alternating current than with direct current. For this measurement alternating current between 110 volts and 220 volts is sufficient. When measurement is done with alternating current the permissible deviation of the impedances of single poles is about ± 5 per cent. Testing with alternating current can only be done when there are no metallic parts inside the coils operating as short-circuited windings, for example, coil spools.

(*e*) WRONG BRUSH POSITION. The effect of the disposition of the brushes on the voltage can best be observed at no-load, particularly if the brushes are very far out of the neutral zone. The proper placing of the brushes is discussed in Chapter V, para. 6 (*e*).

(*f*) AIR GAP IS TOO LARGE. This trouble rarely occurs, but it may happen that after the pole coils have been repaired the field is reassembled and the pole liners omitted.

4. A.C. Generator gives Too Small Voltage at No-load. (*a*) TROUBLE IN THE EXCITER. In every case the exciter should be tested first. In paragraphs 1 and 3 the various troubles which may occur in exciters are indicated.

(*b*) SPEED IS TOO LOW. The possible causes of this trouble are the same as for d c. machines which are discussed in para. 3 (*a*).

(*c*) ROTATING FIELD HAS WINDINGS EITHER CROSS-CONNECTED OR SHORT-CIRCUITED. Crossed connections of the poles can only occur when, after repair, the field coils are either replaced in a reversed position or the connections are reversed. Cutting out of poles by short circuits is possible if both leads can make contact. Both troubles cause not only voltage drop but vibration. Machines having parallel circuits in the stator winding may, in addition, have large circulating currents.

The method of determining the faulty pole is outlined in para. 3 (*c*) and (*d*).

(*d*) ROTATING FIELD HAS SHORT-CIRCUITS BETWEEN TURNS OR LAYERS. These are only apparent at low voltage if a large

portion of the whole winding is short-circuited as a result of the trouble. In addition, more or less vibration occurs on excitation which with increased excitation disappears. The method of finding the fault, place is outlined in Chapter II, para. 6 (*c*). If a sufficiently high a.c. voltage is available, say 380 volts, all poles can generally be connected in series, otherwise they must be divided into groups by undoing the pole connections, or else the poles must be measured singly. When measuring with alternating current the rotating field should, if possible, be dismantled from the stator. Otherwise, considerable voltages may be induced in the stator winding.

It is appreciably more difficult to locate a pole short circuit which only occurs as a result of the centrifugal force caused by the rotation. Here the resistance is measured with direct current, while the rotating field is run at different speeds. The sudden change of the resistance on reaching a certain speed shows when the short circuit occurs. Para. 6 (*c*) of Chapter II describes the method of locating the faulty place.

(*e*) STATOR WINDING IS WRONGLY CONNECTED. This is only likely to arise after repair when single coils are reverse connected. To determine the fault, careful measurement of the individual voltages of the winding phases is necessary.

Another possible but unlikely cause is that a three-phase stator winding may have been connected in delta instead of in star. The terminal voltage of the generator in this case only attains slightly more than half its proper value.

CHAPTER IX

TROUBLES IN D.C. GENERATORS WHETHER OPERATING SINGLY OR IN PARALLEL

1. Excessive Voltage Variation. The terminal voltage of shunt wound generators drops with increasing load, if the field regulator is unchanged. The voltage drop from no-load to full load for self-excited generators usually amounts to between 10 per cent and 20 per cent, according to the size of machine and the number of poles. For separately excited generators, it should only be between 5 and 15 per cent.

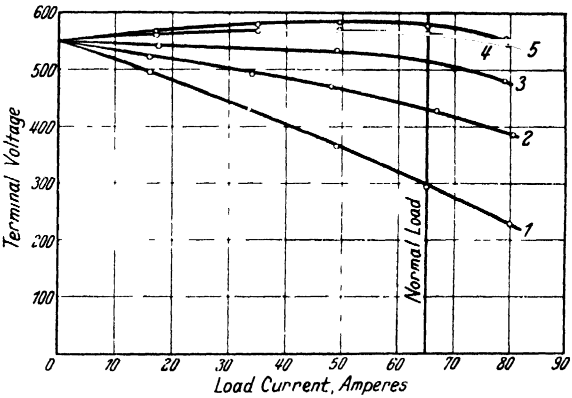


FIG. 90. RELATION BETWEEN TERMINAL VOLTAGE AND LOAD CURRENT FOR DIFFERENT BRUSH POSITIONS OF A D.C. SHUNT GENERATOR WITH INTERPOLES FOR 36 kW. 550 VOLTS

(1) Brushes displaced forward 4 segments. (4) Brushes displaced backwards 2 segments.
(2) Brushes displaced forward 2 segments. (5) Brushes displaced backwards 4 segments.
(3) Brushes in the neutral zone.

(Total number of segments per pole 48.)

If when a d.c. generator is put on load the voltage suddenly drops so that the excitation has to be increased beyond the normal limit, one of the following troubles may be responsible.

(*a*) EXCESSIVE DROP IN SPEED OF THE DRIVING MACHINE. An abnormal voltage change may be due to too great a drop in the speed of the driving machine when put on load. The cause of this may be defective governor gear of the prime mover, insufficient water, or insufficient steam. The slip in

transmission gear such as belts, ropes or friction drives. with increasing load is another possible cause. If an electric motor is used for driving the generator, troubles in this may cause abnormal drop in speed with increasing load.

(*b*) INCORRECT BRUSH POSITION. Wrong brush position on d.c. generators is not particularly noticeable at no load as long

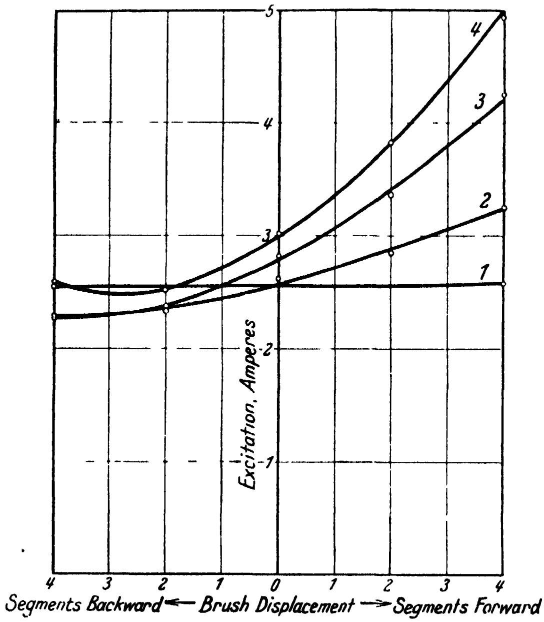


FIG. 91. RELATION BETWEEN EXCITER CURRENT AND BRUSH DISPLACEMENT WITH CONSTANT LOAD AND CONSTANT VOLTAGE FOR A SHUNT WOUND GENERATOR WITH INTERPOLES FOR 36 kW. 550 VOLTS

(1) At no-load. (3) For full load.
(2) For half load. (4) For 5/4 load.

(Total number of segments per pole — 48)

as the brush displacement is not more than 5 per cent to 8 per cent of the pole pitch. On load, however, there is a pronounced effect and brush displacement out of the neutral zone in the direction of rotation will increase the voltage drop between no load and full load. Too small voltage of a machine when on load can therefore arise from brush displacement. In Fig. 90 curves are drawn which show the variation of the terminal voltage of a self-excited d.c. machine with different brush positions, the field regulator being unchanged. Fig. 91

shows the field current necessary to keep the terminal voltage constant with constant load and various brush displacements. It can be seen that considerable brush displacement requires a large increase in the excitation current to keep the machine voltage at its proper value. Even if the commutation would permit a further displacement of the brushes, the field winding

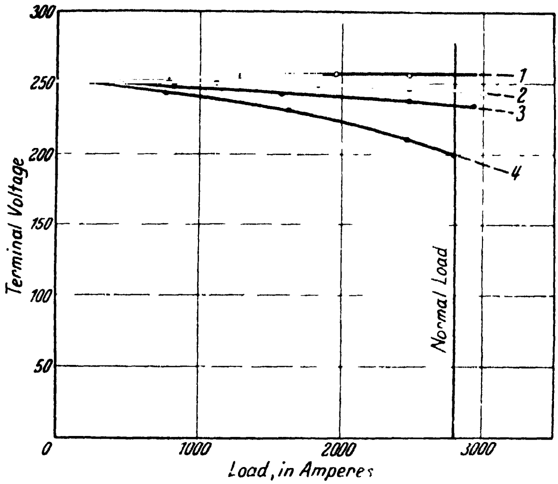


FIG. 92. RELATION BETWEEN TERMINAL VOLTAGE AND LOAD CURRENT OF A SEPARATELY EXCITED D.C. GENERATOR FOR 700 kW. 500 R.P.M.

(1) With full compound winding. (2) With half compound winding. (3) Without compound winding. (4) With full reversed compound winding.

would probably become overheated. Separately excited and compound wound machines behave in exactly the same way as regards brush displacement and excitation.

When d.c. armatures are repaired or rewound, the armature winding may be changed by having the leads from one slot connected to a segment different from before. This means that the neutral zone then comes in a new place, and if the original brush position is maintained, it is equivalent to a brush displacement and may cause too great a voltage drop on load.

(*c*) WRONGLY CONNECTED COMPOUND WINDING. In the case of compound wound d.c. machines, the voltage may drop, remain constant, or even rise between no-load and full load according to the strength of the compound winding. Machines

with these characteristics are referred to respectively as *under-compounded*, *level compounded*, and *over-compounded.*

To make this point clear, Fig. 92 gives curves showing terminal voltage in relation to load current of a d.c. generator of 700 kW. output, operating as a pure shunt wound generator, with separate excitation and as a compound generator with normal and with only a small degree of compounding. This alteration was done by connecting a resistance in parallel with the compound winding. For certain drives a reverse compound winding may even be necessary. The voltage drop between no-load and full load is then even larger than it is when operating as a pure shunt wound machine. Curve 4 shows the variation of the terminal voltage with reverse compounding.

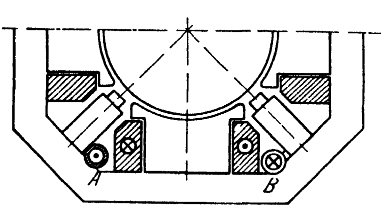


FIG. 93 FIELD WEAKENING EFFECT OF MAIN CURRENT CONNECTIONS

A compound wound generator may therefore exhibit too great a voltage drop if the compound winding has an insufficient number of turns, if its diverting resistance is not of the correct value, or if it is reverse connected. When properly connected, a compound winding should add to the effect of the shunt winding. To test if this is so, the generator with its compound winding switched out is loaded and the field current required to generate the rated voltage measured for any desired load current. Afterwards the experiment should be repeated with the compound winding connected in circuit for the same voltage and load current. If less field current is required with the compound winding, the compounding connection is correct.

(*d*) WRONGLY CONNECTED INTERPOLE WINDING. This fault also produces a large voltage drop on load and is characterized by much sparking. Chapter V, para. 2, deals with the correct connection of the interpole winding.

(*e*) MAIN CURRENT LEADS WRONGLY ARRANGED INSIDE THE MACHINE. In machines for heavy currents and with few poles, a reverse compounding effect may occur due to the wrong arrangement of the main current leads from the brushes, as shown in Fig. 93. The brush leads *A* and *B* pass on the left and right of a magnetic pole and, with the direction of current shown, produce a reverse compounding effect. Hence, the

voltage variation on load is increased. If the current flow is reversed, a compounding effect occurs due to the leads *A* and *B*. When such leads are dismantled, it is important that the connections are afterwards assembled in the proper manner. This is particularly so when the leads were in the first instance taken in parallel through the same interpolar space.

(*f*) Excessive Contact Resistance on the Commutator and in the Leads. Machines for very low voltage and high currents, such as are used in electro-chemical works, may have excessive voltage drop owing to the raising of the commutator contact resistance due to tarnishing and oxidation of the commutator surface or the use of the wrong grade of brush, as well as rough running of the brushes, whether due to an out-of-round commutator or high mica segments. In the case of such special machines, with very low rated voltage, these troubles alone are sufficient to reduce appreciably the terminal voltage. The replacement of metal graphite brushes by carbon brushes considerably increases the contact resistance on the commutator, and usually overheating occurs simultaneously. Badly made connections in the main current circuit or in the leads may become oxidized as the machine continues in service and also increase the voltage drop between the machine and the load.

2. Fluctuations in the Load Current. Variations of this kind, unless caused by the consumer, can generally be traced to the drive. The governor gear of the driving machine may not be operating properly or the transmission gear, such as pulleys, ropes or friction drives, may from time to time exhibit increased slipping. The prime mover also may be affected by the sudden loading of driving motors connected on the supply. In addition, bad contacts in the exciter circuit may cause periodical variations in the load currents.

3. Unstable Load Sharing with Parallel Operation. The proper distribution of the load is achieved by means of the excitation in the case of shunt and compound wound generators operating in parallel. If the voltage variation between no-load and full load of one of the paralleled generators is very small, the slightest change in its excitation will produce a large load variation. If peak loads have to be taken, this machine will also take the main part. The cure for this is to increase the voltage drop, which is usually done by a suitable displacement of the brush rocker.

Compensated machines have a smaller voltage variation than machines without compensating windings. If both compensated and non-compensated machines are working in parallel, the compensated machines should usually have their voltage variation increased by brush displacement. Unstable load distribution may also arise as a result of too large steppings of the field regulators, so that a small adjustment of the regulators causes a large alteration of field current.

When large temporary variations in the load current occur on parallel connected generators without any obvious cause, they are generally due to bad contacts in the excitation circuit, whether in the field regulator or the connecting terminals.

To ensure equal load distribution of parallel connected d.c. generators, the following conditions must be fulfilled. If distribution of the load proportional to the normal loading of individual generators is to be automatically achieved without varying the excitation, the parallel connected machines should have the same voltage variation and their driving machines the same speed drop between no-load and full load.

Troubles connected with voltage regulators are discussed in Chapter XXXIII, para. 3 (*a*).

4. Unequal Load Distribution in Double Commutator Machines. In double commutator machines, the load distribution between the parallel connected commutators often varies during operation. Current differences of 10 per cent and more may occur, mostly caused by unequal contact resistances on the commutator and in the leads. The cleaning of one commutator only is sufficient to cause the load distribution to alter quite considerably. In these machines, it is important to use the same brush grade on both commutators and to arrange the leads from the two commutators so that they have the same resistances. In order to ensure proper load distribution to the two machines an adjustable resistance, brought into operation as required, is often inserted in the leads of one commutator. Generally speaking, differences in the current loadings of the two commutators up to 10 per cent will have no adverse effect on the operation of the machine.

5. Equalizing Connections for Compound Generators. In compound machines an equalizing connection (*L* in Fig. 94) of suitable cross-section should always be between the compound windings, otherwise stable parallel operation is not possible. If the switches marked 1, which are intended to close

the equalizing circuit, are made single-pole, they must be closed first when paralleling and the switches marked 2 afterwards. When switching out, the switches 2 must first be opened and then those marked 1. The switches 1 and 2 can also be united in a 3-pole switch. When connecting the ammeter *A* in a circuit, it should be noted that it must not be put in the lead from bus-bar to compound winding, since then inequalities in the generator currents cannot be noted, as an equalizing current may flow over the equalizing circuit. In the same way the single-pole overload switch sometimes used in

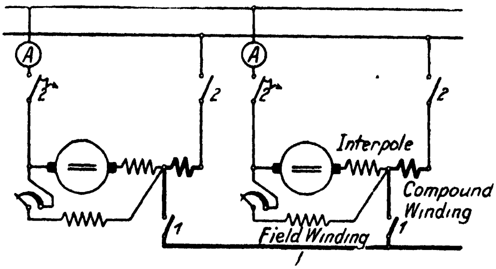


FIG. 94. METHOD OF INSERTING EQUALIZING CONNECTIONS AND CORRECT SITUATION OF THE AMMETER AND AUTOMATIC SWITCH FOR COMPOUND WOUND GENERATORS

the main current circuit must be placed in the same pole as the ammeter *A*, as shown in Fig. 94. If the arrangement is not carried out in this manner, one generator may operate as a motor after the overload switch has been tripped.

6. Adjustment of the Voltage Variation of Parallel Connected Generators by means of Brush Displacement. In the case of small differences in the voltage variation sufficient adjustment can generally be effected by displacing the brushes. The permissible displacement is limited by its effect on the commutation. As already mentioned, displacement of the brushes forwards causes increased voltage drop and displacement backwards reduces it.

7. Adjustment of the Voltage Variation of Paralleled Compounded Generators. An increased voltage drop of compound generators can be produced by the connection of a diverter resistance in parallel with the compound winding, the result being as in curves 1 and 2 of Fig. 92. In large machines the resistance of the compound winding is very small, and sufficiently small parallel resistances can be made of copper cable

or strip, which should be divided into suitable lengths by experiment. Very often a diverter resistance is provided with the machine as a spare. Another expedient is to short-circuit the compound winding of a few poles, but care must be taken to see that the short-circuited poles are symmetrically distributed.

CHAPTER X

TROUBLES IN A.C. GENERATORS WHETHER OPERATING SINGLY OR IN PARALLEL

1. Excessive Excitation on Load. (*a*) Low Power Factor. In an a.c. generator, the voltage variation between no-load and full load and at the same time the field current, depend very much on the wattless load; and thus on the power factor. Increasing the wattless load necessitates increased field current. The chief cause of too great a field current on load can therefore be attributed to too great wattless load. Fig. 95 contains curves for a three-phase generator giving the variation of the field current with the apparent load at a constant power factor, and also a curve showing the dependence of the field current on the power factor with full load and rated voltage If the voltage variation is plotted against the power factor, a curve is obtained like that in Fig. 96.

It can be seen from the curves that in a range of power factors between 1·0 and 0·7 lagging, the exciter current shows a marked increase, while for power factors between 0·7 and 0·4 it increases very little more. If, for example, a generator supplied to operate with a power factor of 0·9 lagging has to give full apparent load and voltage at only 0·6 power factor, the excitation current must be increased to a degree likely to result in overheating of the rotating field winding. When it is found that an a.c. generator is no longer supplying the right voltage, the power factor at which it is working must always be taken into account before a correct conclusion can be reached

(*b*) Speed Too Low. If the speed of a generator decreases very much the network frequency may have changed, or when the generator is running not paralleled, it may be that due to troubles in the driving machinery the rated speed on full load cannot be maintained and the exciter current is increased too much in an endeavour to maintain the voltage.

2. Fluctuations of the Load and the Load Current. Power and current fluctuations, apart from those caused by the consumer, may be due to troubles in the driving machines. In hydraulic turbines sticking of governor gear, slipping of the driving belts, or too great play on gear drives may cause

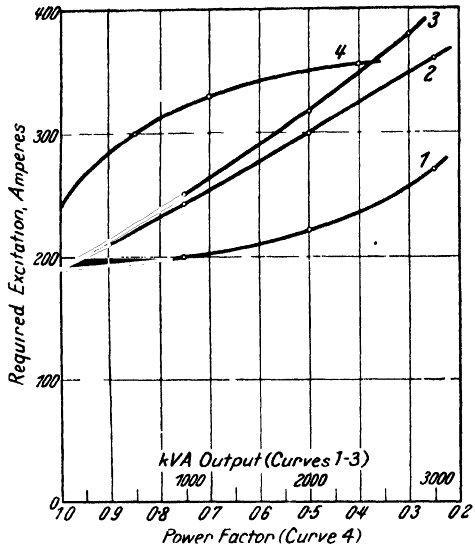


FIG. 95. RELATION BETWEEN THE EXCITER CURRENT OF AN A.C. GENERATOR AND THE LOAD. POWER FACTOR AND VOLTAGE CONSTANT.

(1) Cos ϕ = 1. (2) Cos ϕ = 0.7. (3) Cos ϕ = 0.4.

(4) Relation between exciter current and power factor for rated voltage and rated output.

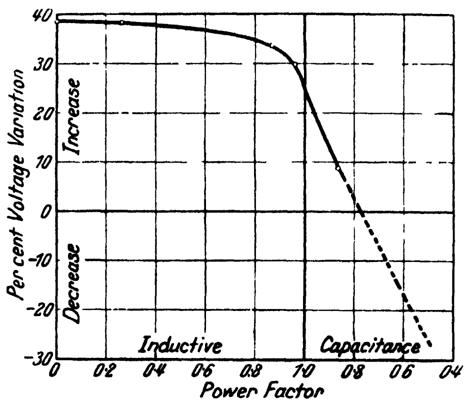


FIG. 96. RELATION BETWEEN VOLTAGE VARIATION FROM RATED LOAD TO NO-LOAD AND POWER FACTOR FOR AN A.C. GENERATOR FOR 13 000 kVA.

temporary variations in output. In motor-generator sets driven by asynchronous motors, troubles may occur in the rotors of these motors. (See Chapter XIV, para. 1.)

Causes of trouble arising in the generator itself include rotating fields that are very out-of-round, usually in conjunction with an out-of-round stator, troubles in the exciter and on the slip-rings due to temporary breaks in these circuits or due to vibrating contacts in the field regulator, or temporary short circuits in the rotating field.

3. Unequal Load Distribution with Parallel Operation. While in the case of d.c. generators operating in parallel, an increase in the excitation and thus in the terminal voltage increases the proportion of load taken, an a.c. generator operating in parallel does not alter its output when the excitation is increased. Alteration of the excitation only affects the wattless load, and the effective output can only be regulated by altering the output of the driving machinery. To achieve automatic sharing of the effective output of generators operating in parallel, the governor gear of the driving machines must have the same characteristics, and if the wattless load is to be automatically and equally shared by the paralleled generators, the voltage regulation must also be equal. When several generators are jointly controlled by having their field regulators mechanically coupled, the exciters should have similar voltage curves and the same voltage regulation, and in addition, the steppings of the field regulators should be the same.

The adjustment of voltage regulators should be looked up in Chapter XXXIII, para. 3 (*b*).

4. Hunting of Machines in Parallel Operation. Synchronous machines will not *hunt* of themselves, and the disturbing force must come from outside. This impulse may be mechanical from the driving machine or electrical from the supply.

Hunting caused by mechanical means is likely to arise in synchronous generators driven by reciprocating engines such as steam engines or internal combustion engines. The torque of these varies periodically during one revolution, and as a result of this variation the driven rotating field is alternately accelerated and retarded, i.e. it varies periodically from a certain average angular velocity. Usually these variations in speed are only apparent as small changes from the average readings shown on the current and wattmeters, and the generator is then said to hunt. The current and load fluctuations

may, however, increase so much that the generator eventually falls out of step. Generally, this trouble cannot be ascribed to the frequency of the torque impulse, since nowadays the manufacturers of driving machines and generators take care that the impulse frequency of the prime mover is sufficiently above the natural frequency of the generator to prevent hunting. On the other hand, troubles in the driving machine or its governor may cause temporary periodical torque impulses having a frequency near that of the natural frequency of the generator, and so cause hunting. Varying steam pressures resulting in different outputs from different cylinders, faults in the governor, or unsuitable natural frequency of the governor, are troubles of this type.

Hunting can also be caused from the supply end when other generators or synchronous motors coupled to reciprocating machines are on the same supply, and when these, as a result of faults either in the driven or driving parts, transmit periodical load impulses. If the frequency of these is nearly the same as the natural frequency of a generator, hunting may develop.

If hunting in a generator reaches a dangerous magnitude, the driving machine and the supply must first be investigated to find if they are the cause. It is desirable in such cases to consult experts from the makers of the prime mover. Often faults can be cured or reduced by changes to the governor gear. If the cause cannot be found in the driving machine or supply, it may be necessary under some circumstances to alter the generator by adding to it as strong a damper winding as possible. The addition of choke coils often effects an improvement but these also increase the voltage drop. Swinburne and Kolben suggest for certain cases the building in of equalizing reactors.*

5. Circulating Currents in Parallel Operation. When the excitation of generators working in parallel is properly adjusted no circulating current will flow between the machines provided the wave forms are not appreciably different. If, however, machines with very different wave forms have to work in parallel, even when the excitation is correct, circulating currents of harmonic frequencies will occur.

In modern machines there are usually only quite small differences between wave forms, so that such troubles rarely

* Kittler: *Wechselstrommaschinen*, 1910, Bd 3, p 265 (in German)

arise. When, however, modern machines have to run in parallel with old types, excessive circulating currents may occur, and as it is usually not practicable to reconstruct the old machine, equalizing reactors should be added as already mentioned in the previous section.

A.c. generators operating in parallel with the star points brought out to provide the a.c. supply with a neutral conductor may have wave forms differing very greatly from one another, which give rise to circulating currents over the bus-bar neutral conductors. The following is an actual example of this An old three-phase generator for 57 kVA., 200 volts, 164 amperes, was running in parallel with a three-phase generator of very recent design for 170 kVA., 200 volts, 490 amperes. Even with no load on the generators and with the generator cut off from the supply, there occurred a circulating current of triple frequency which, with excitation to give normal voltage, reached a value of 105 amperes.

By the addition of a suitable choke coil, this circulating current was reduced to the more reasonable value of 5 amperes. When measuring circulating currents of high frequencies it should be noted that the usual types of instruments may register incorrectly. Hot-wire instruments are not affected.

6. Reversal of Polarity and Demagnetization of Exciters. If the field of an exciter is quickly decreased, or even interrupted and switched in again after an interval of only a few seconds, a reversal of the exciter polarity may occur as a result of the effect of the magnetic energy of the main rotating field. This can best be explained by reference to Fig. 97 (*a*) and (*b*). The arrows show the direction of the current in the main rotating field, and the exciter armature and field winding. When in normal operation, the rotating field is consuming the current (Fig. 97 (*a*)). If the shunt regulator is moved to give a marked increase in the resistance, or if the circuit of the exciter field winding is broken, and then closed again, the generated voltage of the exciter decreases, the exciter current at the same time decreasing rapidly, while the main field flux variation, as a result of the decreasing current in the rotating field, tries to maintain the current. Thus when the interruption time and re-excitation time of the exciter reach a critical value, a new direction of current may be established as in Fig. 97 (*b*). The rotating field, instead of being a current consumer, is for a brief time a current producer and forces through the exciter field a

reverse current causing the exciter to build up with reversed polarity.

Reversal of the polarity depends very much on the brush placing of the exciter and the time taken for the switching out and switching in again of the field windings.

Instead of having reversed polarity the exciter may merely become demagnetized. Its residual voltage is so reduced by this that it is no longer sufficient with the resistances existing in the exciter circuit to establish self excitation. Reversal of

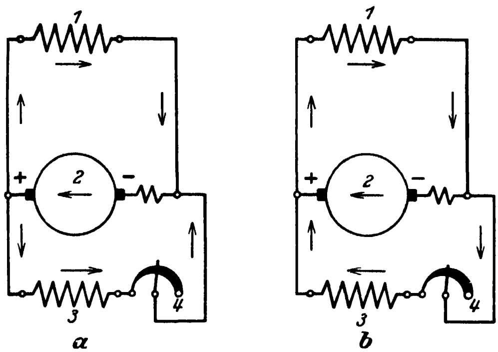


FIG. 97. REVERSAL OF POLARITY IN AN EXCITER

(a) Current path for normal operation.
(1) Rotating field winding.
(2) Armature of exciter.
(b) Current path during reversal.
(3) Field winding of exciter.
(4) Field regulator.

polarity may, in addition, be caused by the interaction between the generator stator and the main field which occurs at sudden short circuiting of the stator winding of a generator.

Various measures can be taken to prevent reversal of polarity and demagnetizing—

(i) The brushes on the exciter may be displaced opposite to the direction of rotation as far as is practicable without spoiling the commutation. Generally, a displacement to the extent of one or two segments is sufficient.

(ii) An auxiliary compound winding may be introduced on the field winding of the exciter, which supports the effect of the shunt winding.

(iii) Short-circuited turns may be placed round the field poles of the exciter.

(iv) The duration of time between switching out and switching in again of the excitation may be lengthened, and the too rapid

increase in shunt resistance may be lessened by slowly adjusting the field regulator. The maximum time that should be allowed to elapse before the shunt excitation is switched in again may be simply determined by experiment. Generally, an interval of between 10 and 30 sec. is sufficient.

CHAPTER XI

TROUBLES IN STARTING-UP AND OPERATING ROTARY CONVERTERS

1. Troubles in Starting. The factors which may impede or entirely prevent the starting of a rotary converter vary according to the method of starting. On the alternating current side, asynchronously started converters behave like synchronous motors. The starting troubles described in Chapter XII, para. 5, may therefore also occur on converters.

In converters which are started by a special asynchronous motor, troubles may originate in the motor as set out in Chapter XII, para. 3. On the direct current side, converters may have the starting troubles described in Chapter XII, para. 2.

(*a*) STARTING VOLTAGE IS TOO LOW. The starting voltage for rotary converters which run up to speed asynchronously is usually between 20 and 30 per cent of the normal a.c. voltage. It frequently cannot be made as high as might be desired on account of starting current or, in the case of converters which run without brush-raising gear, because of sparking.

Apart from too low supply voltage and faults in the starting transformer, the starting voltage may be too low due to excessive losses in the leads to the machine. This, however, is very rare and almost always occurs with heavy current converters which are usually started by an asynchronous motor. On such units the starting currents on the alternating current side may reach values of many thousands of amperes, and when the bars are wrongly arranged quite considerable inductive voltage drops may occur. The tapping voltage may be reduced by a few volts and the converter fail to start. When installing such heavy current conductors, care must be taken to construct the leads to and from with the least possible drop and to prevent, as far as practicable, any loss of volts. Also the individual parallel bars of each phase must be intermingled, as shown in Fig. 98. For the usual voltages, the differences can be kept extremely small. The length of the leads should be a minimum. In such sets the transformer and converter should

be fixed very near to one another, and if the strips have to be taken through iron casings or floor coverings, the plates must be slotted; or else non-magnetic covers used.

The lead losses described also reduce the direct current voltage in normal operation. At the higher voltages, the influence is, however, not so great.

(*b*) Field Winding has Excessive Voltage. If rotary converters are started from the alternating current side with the field winding open, high voltages may be induced in the field coils. This may cause flash-over of the field coils to the iron or the adjacent winding parts, as well as puncture between single layers and turns of the field coils. When using this procedure for starting up, the field winding must always be short-circuited through the field regulator. The best position is usually that which happens to correspond to the excitation for normal operation at unity power factor.

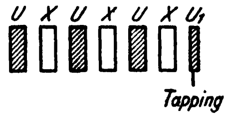


Fig. 98.
Intermingling of In and Out Leads of One-phase for Six-phase Heavy Current Converter

(*c*) Blackened Commutator. Asynchronously started converters may have commutator segments blackened at points equally spaced round the commutator. This blackening depends to some extent on the magnitude of the starting current but also on the brush grade, and usually disappears quickly after subsequent operation of the machine. With excessive but equally spaced burning, either of single or many segments—for example, every second, third, or fourth bar—the first thing to be considered is whether the starting voltage has been raised too high or whether the wrong grade of brush is fitted. For the case of marked burning of individual segments or segment groups, traceable to irregularities in the pole distribution or the slip-ring connections, see Chapter V, para. 6 (*m*) dealing with winding faults in the armature.

(*d*) Other Causes of Starting Troubles. In addition to faults in the supply or in the starting transformer such as open circuits or wrongly connected leads, the starting may be spoilt by open circuits or short circuits in the armature between layers or turns, or in the damper winding, or by short-circuited field coils.

Open circuits may be due to the breaking of a slip-ring lead, or wearing out or sticking of slip-ring brushes. Less common

causes are the unsoldering of the winding ends or even a break in a conductor.

2. Troubles when Synchronizing Asynchronously Started Converters. (*a*) STARTING VOLTAGE IS TOO LOW. In rotary converters, just as in synchronous motors, the synchronizing can be prevented or hindered by too low a starting voltage on the a.c. side. In addition to faults in the supply or starting transformer, wrong choice of tapping—particularly in heavy current converters, or too great voltage drop in the leads, can lower the starting voltage. This possibility was discussed in Chapter XI, para. 1 (*a*).

Rotary converters synchronize best at a starting voltage of 15 to 25 per cent of the rated voltage on the a.c. side.

(*b*) FIELD WINDING IS WRONGLY CONNECTED. A rotary converter can be brought into synchronism only with great difficulty or not at all if the leads of the field winding are reversed. If, however, synchronism has already been reached, at a certain excitation the converter will again fall out of step. A converter which is not in synchronism will spark on the commutator at the slip frequency.

(*c*) EXCITER CIRCUIT IS INTERRUPTED. A break in the excitation circuit, whether in the field winding or field regulator, will generally prevent a converter from synchronizing.

(*d*) DAMPER WINDING HAS TOO HIGH RESISTANCE. The synchronizing will be prevented when the resistance and consequently the slip are too great due to overheating, bad contacts, or breaks in the bars of the damper winding.

(*e*) POLARITY IS WRONG ON THE D.C. SIDE. In the case of a self-excited converter started from the a.c. side, the polarity existing on the d.c. side depends entirely on chance. If a converter has been synchronized with the wrong polarity, the rotor must be allowed to slip a pole pitch to achieve the right polarity. This slipping into the proper pole position can be done by two methods.

(i) By breaking the a.c. leads for a short time.

(ii) By switching out the field winding for a short time, during which the rotor slips out of the wrong synchronism, and on attaining the new position is synchronized again with the field winding properly connected. The moment of switching can be easily found by observation with a d.c. voltmeter, after a little practice. It is obvious that this switching out must be done in the starting connection with the tap-voltage.

(*f*) Current Surges Due to Switching the Full Supply Voltage on the Excited Converter. With this switching process, the conditions are the same as for switching in a synchronous motor (see Chapter XII, para. 6). With self-excited converters the field regulator should from the start be kept in the normal operating position, since the necessary excitation for full supply voltage cannot be obtained because the self-excitation and the d.c. voltage are reduced on the starting up step. With separately excited converters the best excitation is usually set in the starting position.

In converters, as in synchronous motors, the switching-in surge can be very much reduced by using choke coils as in Fig. 99. It is, however, necessary to wait for a few seconds in the intermediate position when switches 1 and 2 are open. As an example of this, a six-phase converter of 2 000 kW. can be quoted. With immediate switching in without using the choke coils the current surge measured on the slip-ring side amounted to about 90 per cent of the rated current; after waiting 8 sec. a current surge of only about 15 per cent of the rated current was measured.

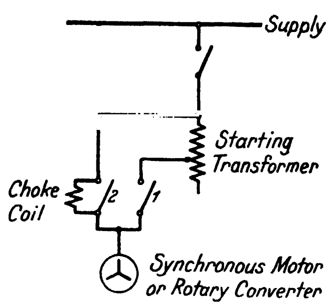


Fig. 99.
Starting Connection with Buffer Choke Coil for Synchronous Motors and Converters

3. Voltage Regulation of Rotary Converters. In rotary converters, the regulation of the d.c. voltage cannot be done solely by varying the excitation but must be effected by adjustment of the alternating voltage. The ratio $\frac{\text{a.c. voltage}}{\text{d.c. voltage}}$ does not vary greatly from no-load to full load and amounts for three-phase converters to 0·6–0·7 and with six-phase converters to 0·7–0·8.

The regulation of the a.c. voltage may be effected by tapped transformers, induction regulators, booster machines, or by varying the excitation when there are transformers or choke coils having sufficient reactance on the a.c. side.

This last type of voltage regulation causes an increase in the copper losses due to the increased wattless current. The reactance of the transformer and of the choke coils is therefore chosen as large as possible in order to obtain sufficient

regulation with the least wattless current, that is to say, with a high power factor. In general, a wattless current of the order of 30 to 40 per cent of the rated wattful current is permissible. The output must, however, be reduced by 10 to 20 per cent to allow for the increased heating due to the higher current.

When troubles arise in connection with the regulation of the d.c. voltage, the voltages on the a.c. side should be measured in the first place. When regulating with tapped transformers, the trouble may be due to the regulator switch sticking, wrong keying of the driving motor, or wrong placing of chains or ropes between switch and motor. The working instructions for the tapping switch will contain precise directions for fixing the driving parts, and chains and gears are usually assembled in their correct positions in the workshop. When regulating with induction regulators a break in the potential winding may be the cause of the trouble. If additional machines are used for regulation on either the a.c. or d.c. side, faults in their field circuits may cause trouble and they must be tested as described above. Troubles may also be caused as described in Chapter VIII, para. 3.

4. Troubles During Operation. (*a*) EXCESSIVE VOLTAGE VARIATION. The voltage drop between no-load and full load in a rotary converter without a compound winding usually amounts to 2–5 per cent. By adding a compound winding, this value can be altered in exactly the same way as for a d.c. machine. A small variation can also be obtained by displacing the brushes, the extent of displacement being obviously limited by its effect on the commutation. Apart from voltage drops on the a.c. side which may become too great on account of the current, the main causes of excessive voltage variation are incorrect brush position (brushes too much displaced), wrong connection of compound and interpole windings, and wrong excitation.

(*b*) UNEQUAL LOAD DISTRIBUTION IN PARALLEL OPERATION. To attain an equal distribution of the load between two converters running in parallel, the voltage variation of the converters must be as nearly as possible the same. Since the voltage variation is influenced also by the voltage drops in associated transformers, (there is a fixed relationship between the a.c. and d.c. voltage of a converter)—the drop in the transformers must be equal and for heavy current converters the drops in the leads must also be equal. The converter can, to

a small extent, be adjusted by brush displacement, displacement of the brushes forward out of the neutral zone increasing the voltage drop, and displacement backwards decreasing it. With excessive voltage drop in a converter, the load on the d.c. side is reduced.

The load distribution on the d c. side can only be properly controlled by the excitation when the converter is connected to the supply on the a.c. side through a transformer, or if suitable additional choke coils are added. The a.c. voltage, and as a result the d.c. voltage and the loading, are raised by over-exciting the converter, while under-excitation decreases them. The increased wattless current increases the copper losses in the converter and on this account the variation in excitation should not be taken too far.

The a.c. voltage itself and consequently the loading of the d.c. side can also be regulated by tapped transformers and induction regulators and by booster machines

(*c*) Circulating Current with Parallel Operation Rotary converters do not run well in parallel unless transformers or choke coils are inserted on the a.c. side. On account of the small internal voltage drops, small differences in the resistances, i.e. the brush contact resistances or the winding resistances, can completely spoil the load distribution by unequal heating. It may even happen that direct currents circulate on the a.c. side. Every converter must therefore have its own transformer to ensure a proper load distribution, and the connection of several converters to a supply all using the same transformer is not practicable. At the same time, it is not permissible to connect star-points of different transformers on the converter side, since this may facilitate the flow of circulating currents.

(*d*) Hunting and Falling Out of Step. A converter will hunt when rapid variations in the loading take place. Short circuits may also cause the machine to fall out of step. Since the field poles of converters are usually laminated, a damper winding is built in to ensure the necessary synchronizing torque. If the damper bars gradually become unsoldered, the resistance of the damper winding is increased, its effect lessened and there is the danger of hunting. In addition, a very much under-excited converter is inclined to hunt, and when this takes place, sparking can usually be observed on the commutator.

(*e*) Racing. When switching off a converter running in

parallel from the a.c. supply without simultaneous disconnection on the d.c. side, the converter, if under excited, may accelerate to a dangerously high speed. For protection against this, centrifugal switches are built in which trip out the switch on the d.c. side as soon as too high a speed occurs, that is, a speed 15 to 20 per cent above the rated speed.

A converter working in the opposite direction from d.c. to a.c. supply which is not paralleled on the a.c. side and thus kept in synchronism, may attain an undesirably high speed with pure no-load operation due to the field weakening effect of wattless current. The same danger exists in this type of converter due to short circuits in the a.c. supply.

5. Parallel Operation with D.C. Machines or Batteries. A converter working in parallel with d.c. machines or batteries takes over the largest part of the load in the case of peak loads, on account of its small voltage variation. To a small extent, equal load distribution can be attained by displacing the commutator brushes. It is often necessary, however, to put on the main poles a weak reverse compound winding or to provide additional choke coils on the a.c. side.

CHAPTER XII

STARTING TROUBLES OF MOTORS

1. Mechanical Causes of Starting Troubles. (*a*) DRIVEN APPARATUS OUT OF ORDER. Sticking or wearing of the bearings due to excessively tight pulleys, obstruction in stone-breaking machinery or mills, erroneously closed exhaust valves of reciprocating compressors, open dampers in exhaust fans or open pressure valves in blowers and pumps, too tight stuffing boxes, and numerous other conditions may cause the required starting torque to be excessively increased. The torque of the motor is then not sufficient to accelerate the machine up to speed, or else, due to increased load, the machine will not operate at full speed. This is particularly common in a.c. squirrel cage motors which, to reduce the starting current, are started with decreased voltage and consequently decreased torque, as when star-delta starters or auto-transformers are used. Also in the case of asynchronous motors with starting resistances on the rotor, having the steps short-circuited successively by centrifugal switches during acceleration, the switching out of one or more steps may be prevented due to too great a load torque. The motor "locks in" at too low a speed and there is the danger that the resistances in circuit will be burnt out. When the drive has many bearings, the torque may be increased excessively solely because the machinery has been stationary for too long.

(*b*) MECHANICAL FAULTS IN THE MOTOR. The most important mechanical faults in the motor itself are rubbing of the rotor due to melting out of the bearings or bent shaft, seized up bearings, or jammed rotor.

The bearing clearance of motors may become too great due to ingress of sand, cement, or metallic dust when refilling with oil; these act as grinding agents and cause wear on the bearing and shaft. The ingress of such foreign matter into the bearing is generally due to carelessness in dirty and dusty situations resulting in oil reservoir covers, filling holes or bearing caps being left open. Less often the trouble is due to unsuitable bearings. Too much bearing clearance leads eventually to so much displacement of the rotor that on account of the

increasing unbalanced magnetic pull it "pulls over." Asynchronous motors, which generally have a small air gap, are prone to this trouble. The cause for the rubbing of a rotor can also in some cases be traced to too great a deflection of the shaft caused by excessive pull on the belt, which may arise as a result of using too small a pulley.

Difficulty in starting due to the presence of foreign bodies which have been drawn into the air gap between stator and rotor seldom occur. When they do arise, it is generally as a result of the carelessness of the erection or maintenance staff.

If a rotor commences rubbing, a loud humming combined with vibration is always apparent. Stator and rotor laminations are polished where they rub, and exhibit signs of heating.

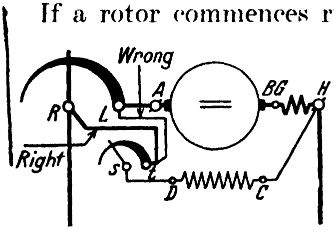


FIG. 100 WRONG AND RIGHT CONNECTION OF THE FIELD WINDING OF A D.C. SHUNT WOUND MOTOR

2. Starting Troubles in D.C. Motors. (*a*) LEADS AND MAIN CIRCUIT ARE BROKEN. It is not necessary to discuss here the most important faults in the leads such as blown or improperly fixed fuses, burnt contacts in switches, or open circuits in starters. Any practical man will always examine these parts of the plant first if starting trouble arises. Breaks in the main circuit may also occur in the interpole or compound winding, or in the connections between the brushes and armature windings, if the brushes are not resting on the commutator.

(*b*) DAMAGED SHUNT REGULATOR. In d.c. shunt motors when the field regulator or connections to the field winding have an open circuit, the motor will not carry load and if unloaded it may run away. This danger is even greater with compound wound motors having a very strong compound winding. These faults may develop while on full load, in which case the current taken is very large and the fuse blows or the protective devices are tripped.

(*c*) WRONG FIELD WINDING CONNECTIONS. D.c. motors also may not start if they are wrongly connected. If, for example, the leads to the field winding are, as in Fig. 100, wrongly connected inside the starter, so that the field winding receives only a small voltage, the poles are only slightly excited and the motor cannot develop its full torque. When switching out the starter the current in the field winding increases, and

an unloaded motor will start and then work properly when the short-circuit position of the starter is reached. Fig. 100 shows also the proper connection. In starters with three terminals, this fault is also likely to occur as a result of the main leads being wrongly connected. For example, the supply may be incorrectly connected on R and the motor on L, instead of the proper arrangement, as shown in Fig. 101 (*a*) where the armature terminal A is connected to R and the supply to L.

Another wrong connection is shown in Fig. 101 (*b*). Here the leads of the motor are crossed over, the motor will not carry any load, and will even burn out on no-load.

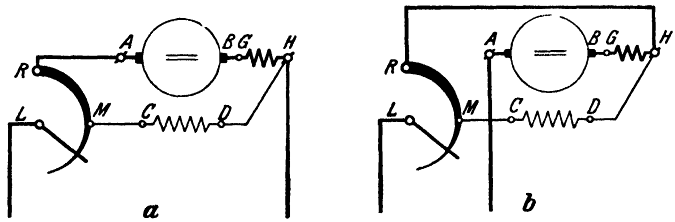


FIG. 101. (*a*) RIGHT AND (*b*) WRONG CONNECTION OF A D C SHUNT WOUND MOTOR AND STARTER

(*d*) FIELD WINDING OPEN-CIRCUITED OR WRONGLY CONNECTED. The torque is very much reduced by a break in the field winding of a d.c. motor of any type, as well as by incorrectly connected or partially short-circuited field coils. When the field is open-circuited, the unloaded motor will "run away" with considerable sparking and tend to burn out. If the motor is sufficiently heavily loaded, it will not start at all and will take a large current. On switching out further resistance steps on the starter, the protective gear will trip out. If single poles are reverse-connected or short-circuited, the motor will either fail to move or accelerate rapidly, according to the load. In the latter case, however, it will exceed the rated speed and take an abnormal current.

(*e*) FIELD WINDING HAS SHORT CIRCUITS OR BREAKDOWNS TO EARTH. Due to the various types of short circuits between turns or layers in the field winding enumerated in Chapter VIII, para. 3 (*d*) as well as the breakdowns between the iron and other windings shown diagrammatically in Figs. 86 and 87. the field can be so weakened that the motor either will not start even at light load. or will reach too high a speed in its unloaded state.

(*f*) SHORT-CIRCUITED OR OPEN-CIRCUITED ARMATURE WINDING. Short circuits or open circuits in the armature winding will also cause the motor to fail to start or prevent it from reaching its normal speed. When there is a short circuit in the armature, excessive current is taken, there is rapid overheating of the short-circuited layers or coils at the affected place, and the associated commutator segments spark. The armature of the stationary motor can then usually only be moved in jerks. With an open circuit in the armature, considerable sparking on the commutator segments belonging to the damaged coil also occurs and frequently, as a result of this, the mica between the segments is burned.

(*g*) COMPOUND WINDING WRONGLY CONNECTED. When the main current winding of a compound motor is wrongly connected, the shunt winding and compound winding may partially cancel one another, resulting in a decreased starting torque.

It is convenient to describe here how to determine if the connection of the compound winding is correct. The motor should be uncoupled, or with belt drive the belt may be removed, and it should then first be allowed to run with normal connection with the shunt winding in circuit and the direction of rotation noted. Afterwards a lead to the shunt winding is broken and the starter switched in again, beginning from standstill and proceeding until the motor begins to rotate definitely in one direction, either by itself or after a push. Since the motor has a tendency to run away, it must be immediately switched out after the direction of rotation is established. If necessary, in this experiment the current may be increased for a short time to normal current. If the motor still turns in the same direction as before, the connection is right. If this is not the case, the compound winding must be reversed. It must also be noted in this connection that, when altering the direction of rotation of a compound motor, the shunt winding terminals and the compound winding terminals must be changed over simultaneously. The proper connection of the compound winding can also be found by determining the speed drop of a compound motor between no-load and full load. This speed alteration is measured with the supply voltage as nearly constant as possible, first with the compound winding connected in the circuit, and then with it switched out or short-circuited. If it is properly connected, the speed

difference between no-load and full load is greater with, than without, the compound winding.

(*h*) INTERPOLE WINDING WRONGLY CONNECTED. If the brushes are set in the neutral zone a shunt motor, although its interpole winding is wrongly connected, will still run properly, but there is usually considerable sparking.

(*i*) INCORRECT BRUSH SETTING. A considerable displacement of the brushes out of the neutral zone reduces the torque. The starting is either adversely affected or the motor stalls. In any case, there is usually excessive sparking on the commutator.

If the brushes of a shunt motor are displaced backwards out of the neutral position and the motor is under-excited, it may happen that on reaching a low speed it stalls, and afterwards its direction of rotation may even change. This trouble usually arises when the field winding is wrongly connected, as in Fig. 100, or when the motor terminals are reversed, as in Fig. 101 (*a*).

The method of setting the brushes in the neutral position is outlined in Chapter V, para. 6 (*e*).

3. Starting Troubles of Asynchronous Motors. (*a*) LEADS ARE OPEN-CIRCUITED OR CROSSED OVER. A.C. motors will not start if there is an open circuit in even one stator lead, but will only move in jerks with a marked humming noise. If, however, the motor is running at normal speed and an open circuit in a lead occurs, it will continue to run with normal torque. Current and slip are, however, so greatly increased that there is the danger of the windings being burnt out unless the motor starter has properly-adjusted protective gear. In Fig. 102 an example is shown of how the output, speed, and current of a motor behave when it is properly connected, and also with an open circuit in one stator lead. In the last case, the motor can only handle 80 per cent to 90 per cent of the rated torque, and takes approximately twice normal current. Motors with star-delta starters may have starting trouble due to mistakes in the connections between motor and starter; for example, the running connection may be in star instead of in delta.

(*b*) LOW SUPPLY VOLTAGE. With much reduced supply voltage, asynchronous motors will still develop sufficient starting torque if enough resistance is switched out in the starter, or in the case of squirrel cage motors with star-delta starting, if these are switched directly on to the delta position.

In the case of squirrel cage motors equipped with auto-transformers, when the starting voltage is too low, the transformer tapping should be altered to a higher value.

(c) OPEN CIRCUIT IN THE ROTOR STARTER. An asynchronous motor, even though it has an open circuit in the connections in the rotor starter, will still run light. It will give 10 to 20

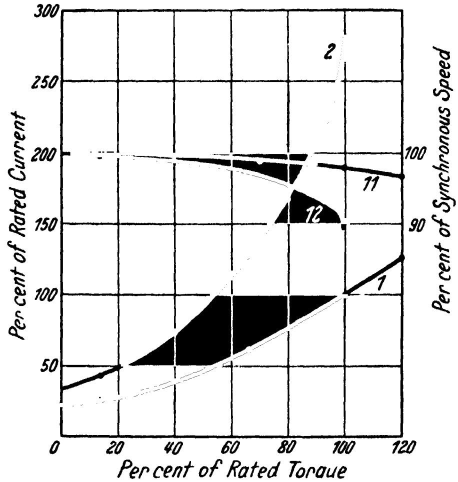


FIG. 102. STATOR CURRENT (1 AND 2) AND SPEED (11 AND 12) OF A THREE-PHASE MOTOR FOR 82 kW RATED OUTPUT, 975 R.P.M.
1 and 11 with three-phase connection. 2 and 12 with one stator lead open circuited.

per cent of the rated torque without drawing excessive current. At higher loads, however, it will stall.

(d) STARTER IS UNSUITABLE. An a.c. motor develops its maximum starting torque at a certain fixed most favourable value of the total rotor resistance. If this value is either exceeded or not reached, the torque is less. Fig. 103 shows the relation between the torque and current of an a.c. motor and the resistance in the rotor circuit. In Fig. 104 the torque of an asynchronous motor is shown relative to the speed with various rotor resistances. It can be seen from this that the speed at which maximum torque occurs varies according to the value of the resistance. The diagram also makes it clear that the starting current peak depends on the point and likewise the speed at which the starter is operated. When wrongly connected, the motor may be switched out by the

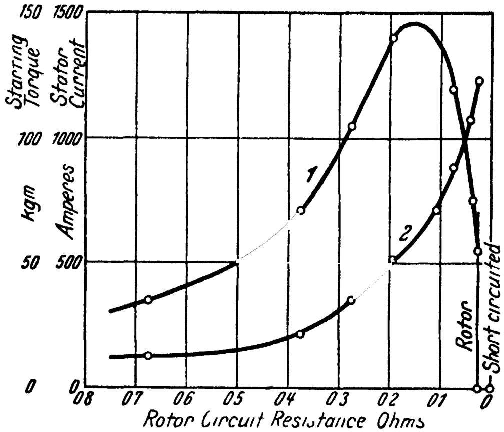


FIG. 103. STARTING TORQUE AND STATOR CURRENT OF AN A.C. MOTOR FOR 55 kW, 220 VOLTS, 1,000 R.P.M. RELATIVE TO THE RESISTANCE OF THE ROTOR CIRCUIT.
(1) Torque. (2) Stator current.

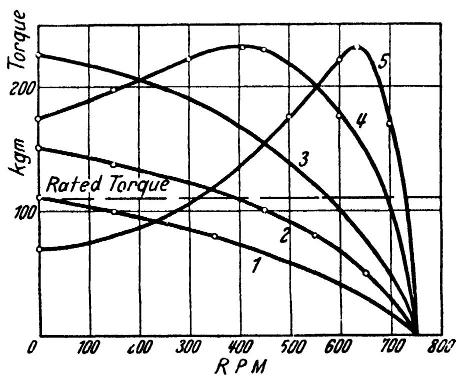


FIG. 104. TORQUE RELATIVE TO SPEED AT DIFFERENT RESISTANCE VALUES OF THE ROTOR CIRCUIT OF AN A.C. MOTOR FOR 80 kW, 500 VOLTS, 750 R.P.M.

(1) Torque with R_{tot} = 40 × rotor resistance
(2) With R_{tot} = 20 × rotor resistance
(3) With R_{tot} = 6 × rotor resistance
(4) With R_{tot} = 3 × rotor resistance
(5) Torque with short circuited rotor

overload trips. In this respect, there is no difference between asynchronous and d.c. motors.

Troubles in liquid starters are described in Chapter XXVIII, para. 3.

(*e*) Stator or Rotor Winding is Open-circuited. With open circuits in the stator or rotor winding, the motor will either not start or else starts with greatly diminished torque, according to the connection of the winding. When the open circuit occurs while the motor is running, it will reduce the maximum torque and increase the current consumption and slip.

If squirrel-cage rotors have a few bars badly jointed the torque may be reduced and starting adversely affected. Loosely soldered coil ends on wound rotors will also spoil the torque, as well as loose contacts on the short-circuiting mechanism. All these troubles can be identified by the fluctuations they cause in the stator current. In low capacity supply systems, flickering of the lamps connected to the same supply may even occur. Sudden humming noises together with vibration of the motor, which become louder and more violent as the motor is loaded, are signs of this type of trouble.

Single-phase asynchronous motors which require an auxiliary winding and special starting apparatus may have the starting spoilt due to open circuits in the auxiliary winding or control gear. Very often in motors of old design which have for starting purposes an electrolytic condenser, starting troubles may be due to crystallizing or evaporation of the fluid.

(*f*) Short Circuits in Stator or Rotor Winding. These short circuits may cause stalling of the motor when on load. While a short circuit in the stator allows the motor to accelerate with decreased torque, a motor with a short circuit in the rotor may not start and can only be moved in jerks. There is then usually marked humming and considerable local heating. The stator current will also vary if a rotor with a short circuit is moved out of its position of rest. Similar phenomena occur when not only single turns and layers are short-circuited but when a whole winding phase is cut out, whether this is due to insulation faults on the coil or phase connections, or to wrong connections on the terminal bar of the motor.

In a.c. motors which are connected to the supply with an earthed neutral, a breakdown to earth of a part of the winding always means a short circuit.

(*g*) INCORRECT CONNECTION OF STATOR OR ROTOR WINDING. This almost always means wrong connection of the winding leads on the terminal bar. A stator winding may be connected in star instead of in delta, which reduces the starting torque to about a third of what it would be with delta connection, and this torque is not always sufficient for starting under load. Motors which are designed for more than one voltage may have their connecting leads wrongly arranged for a voltage higher than the supply voltage. This again means decreased torque, since in a.c. motors the torque varies as the square of the terminal voltage. The wrong connection of the three phases as in Fig. 105 (*a*), in which the beginning and end of one phase are reversed, instead of as in Fig. 105 (*b*), is also responsible for the failure of a motor to start against load. An unloaded motor with this kind of fault will, however, run up to speed, but not smoothly. Unusually loud humming occurs and the stator currents are very unbalanced and even at no-load amount to many times the normal current.

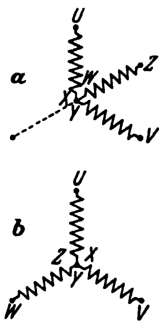


FIG. 105.
(*a*) WRONG AND (*b*) RIGHT CONNECTION OF AN A.C. STATOR WINDING IN STAR CONNECTION

Wrong connection of single coils or coil groups becomes apparent in the same way. Humming and vibration start which, with parallel circuits in the stator, may reach such a degree as to become excessive when the motor is running light. It is generally extremely difficult to trace wrong connections in the stator or rotor. It is essential to have suitable measuring instruments and a source of current of which the voltage can be varied. In Chapter II, para. 8 (*a*), a more detailed survey of such faults was given. All rotor faults have the common characteristic that whether the motor is running or merely rotated by hand, marked fluctuations of the stator current occur.

(*h*) FLASH-OVERS ACROSS SLIP-RING INSULATION. Flash-overs on slip-rings usually arise when switching in the motor with the rotor starter open-circuited. A condition always predisposing to this, however, is the fouling of the insulation by oil, carbon and other dust, or tracking caused by damp or chemicals. As a result of careless maintenance, the brush leads may even be in direct contact. In dirty and dusty situations, the insulation between the slip-rings should be cleaned

periodically, and accumulation of oil on these parts usually indicates that there is a leakage of oil from the adjacent bearing. In this case, of course, the bearing itself should be examined. Large collections of carbon dust in a short time are usually associated with the use of the wrong grade of brush, or the wrong brush pressure. Such causes of trouble and their cure are dealt with in Chapter IV, para. 7.

Many maintenance engineers have the impression that when short circuits occur between slip-rings, high voltages arising at the moment of switching in are the cause of the trouble. This is not the case, however, since when a motor, having its rotor connected to the starter, is switched in, no voltages sufficiently dangerous to cause this trouble can arise in the rotor. One of the causes mentioned above should always be sought.

4. Starting Troubles of Synchronous Induction Motors. Since these motors start as ordinary asynchronous motors, they are subject to the same starting troubles. The synchronizing of these machines is described in para. 6, below.

5. Starting Troubles of Synchronous Motors. The defects in the stator winding described in para. 3, above, causing starting troubles in asynchronous motors, apply equally to synchronous motors. In addition, troubles arise from too low starting voltage or from faults in the rotor. In synchronous motors with salient poles, the starting torque is created by the joint effect of the stator rotating field and the rotor currents. The latter occur either in the solid pole shoes or in special damper windings which are built in the pole shoes for the purpose of increasing the starting torque.

(*a*) Starting Voltage is Too Small. Synchronous motors when starting by means of a tapped transformer have a reduced starting voltage which is not adjustable in practice. With synchronous motors running up to speed light, it amounts to between 20 and 30 per cent of the normal voltage. In motors which have to overcome a certain load torque during starting up, the starting voltage lies between 40 and 75 per cent according to the value of this torque.

The starting voltage cannot in this case be increased to any desired extent, since it is limited by the permissible current peak. In general, it is chosen sufficiently high so that for the worst starting conditions with cold bearings and bad rotor position, at least 10 per cent excess voltage is available. If, however, the supply voltage of a plant drops about 15 per cent

it may happen that the machines will only start up at a very few positions of the rotor, or perhaps not at all. Since the bearing friction decreases greatly immediately after starting, it is often a good plan to turn the rotor round by hand before switching in the machine in order that oil may be drawn on to the shaft inside the bearings. If the supply voltage is permanently decreased, a higher voltage step must be connected on the starting transformer. If this, however, is not practicable, either the transformer must be altered or the starting conditions of the machine improved by arranging a pressure oil supply to the bearings. By supplying a small quantity of oil to the centre of the lower bearing shell, under a pressure of 20–30 atmospheres, the starting voltage required for synchronous motors running up light can be quite considerably reduced. These measures, however, will probably not affect the starting of synchronous motors on load.

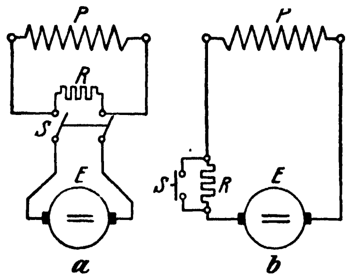


FIG. 106.

SHUNT-SERIES RESISTANCE FOR THE ROTATING FIELD ON STARTING UP A SYNCHRONOUS MOTOR

P. Rotating field winding.
R. Starting resistance.
E. Exciter.
S. Switch.

In a few cases, small synchronous motors are switched on the full supply voltage through choke coils which, when the full speed has been reached, are cut out. In this case also, too large a drop in the supply voltage will make the starting voltage too low. To cure this, the reactance of the choke coils must be reduced, and since such chokes almost invariably have iron cores and air gaps, this is very simply done by increasing the air gap. If this is not successful, however, the number of turns of the coil must be reduced.

(*b*) DAMPER WINDING BROKEN. Damper windings used for starting are made of either copper, brass or bronze. The damper bars are usually riveted to the damper rings and silver soldered. In spite of this, however, heating may cause them to come unsoldered and spoil the starting. The junction pieces between the segments, of which the ring is formed may also have bad contacts or even be left out with a similar result.

(*c*) ROTATING FIELD WINDING IS SHORT-CIRCUITED. As a

rule, synchronous motors accelerate better when their rotating field winding is either left open or connected in series with a resistance of a value several times that of the winding resistance. The starting is usually bad with a short-circuited field. The switch usually inserted between the rotating field and the exciter should be open. Fig. 106 (*a*) shows a typical simplified diagram of the starting connections. If the rotating field during

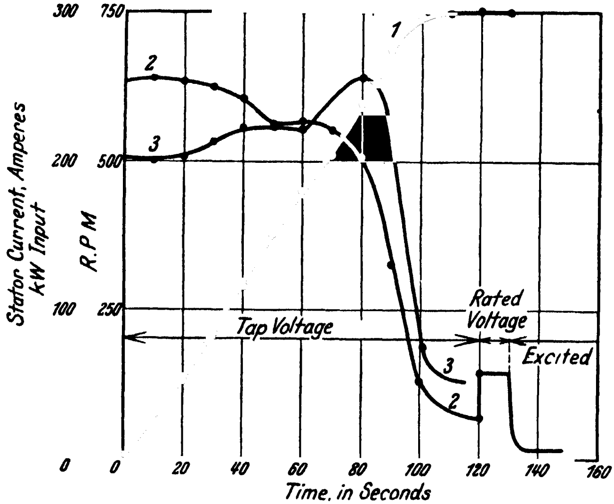


FIG. 107. STARTING OF AN EIGHT-POLE A.C. SYNCHRONOUS MOTOR OF 370 kW.
(1) Speed. (2) Stator current. (3) Power taken.

starting is connected to the exciter, a special starting resistance is usually added, which is cut out on attaining the rated speed as in Fig. 106 (*b*).

The starting can also be spoilt by short circuits between the turns of individual field coils.

In Fig. 107 a few characteristic curves are given. They were taken during the running up to speed of a synchronous motor driving a compressor.

6. Troubles in Synchronizing Synchronous Motors. (*a*) LOAD TORQUE IS TOO GREAT. A synchronous motor can only be synchronized with certainty against a definite maximum load torque. If this is exceeded owing to any trouble on the driven machine, it is no longer possible for the motor to pull into step. Such a cause of trouble may, for example, occur on

compressor and blower drives where the bad sealing arrangements of the piping on the exhaust side cause the compressor to have while accelerating a certain load, and the motor to be too heavily loaded to allow it to synchronize. In the case of pumps, insufficiently closed valves may cause too large an increase in the torque during acceleration.

(*b*) STARTING VOLTAGE IS TOO LOW. The synchronizing of a motor may also be prevented by too low a starting voltage. Synchronous motors which are only used for power factor correction, and consequently run unloaded, will usually pull into step with the correct polarity on reaching the rated speed on the starting step, and without excitation. If, however, with too low voltage this is no longer possible, the machine can always be brought into step by applying the proper excitation. This is not the case for machines which are loaded at the start and which, with applied excitation, must pull into step from a definite slip. Too low a voltage causes an excessive increase of the slip of the motor while it is still running asynchronously, and it cannot then be synchronized.

The synchronizing of synchronous motors on a steady supply is naturally much easier than on a fluctuating supply.

Synchronous machines running up to speed, unloaded, usually pull into step without excitation at about 15 to 25 per cent of the normal voltage. When the running up to speed has to be done under load, the value of the voltage to ensure synchronizing, even with sufficiently small slip, is much higher according to the actual load torque.

According to the starting procedure adopted, the change-over from starting voltage to full voltage may take place in one or two steps. The switching in of the excitation in the latter case is made at that voltage at which the motor previously pulled into step without excitation. When it is permissible from the point of view of current peak, the machine may even be switched on the full voltage and afterwards excited. In order, however, to reduce the peak at switching in, it is better to synchronize the motor first and afterwards switch it on to full supply voltage.

If the starting voltage is actually too low and synchronizing impossible, the transformer must be altered by choosing another tapping. Transformers are usually supplied with two or more tappings to facilitate a raising of the starting voltage by 5 to 10 per cent.

(*c*) Excessive Resistance of Damper Winding. Synchronous motors for starting on load often have laminated poles and a damper winding instead of solid pole shoes, in order to produce sufficient starting torque. The synchronizing of these motors may be made difficult by excessive heating, bad contacts, breaking of bars of the damper winding, or too high resistance and consequently too great slip.

(*d*) Reversed Polarity. In this case, the synchronous machine pulls in to step with the wrong polarity. This condition is recognizable when, after the excitation is switched on, the stator current does not drop to its minimium value at $\cos\phi = 1$. The stator current may even first rise with increasing excitation, exceed a maximum value of 50 to 100 per cent normal current, and then decrease to become a minimum at the proper excitation. At the instant that the stator current reaches its highest value, the rotating field slips back one pole pitch. The current values taken correspond to starting with a voltage of 30 to 40 per cent normal voltage If this takes place at full supply voltage, the stator current is usually larger than the full load current at the moment of slipping of the rotating field.

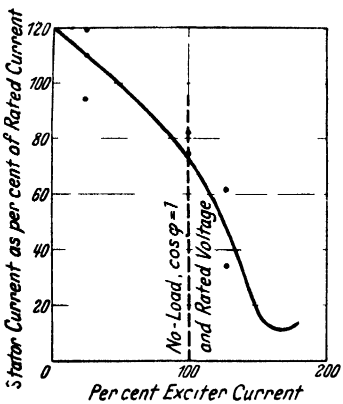


Fig. 108

Relation between Switching in Surge and Excitation of an A.C. Synchronous Motor for 3 000 kVA. Running Light

(*e*) Current Surges on Switching the Full Supply Voltage on the Excited Synchronous Motor. To keep the current surges caused by switching from starting voltage to full supply voltage as small as possible, a suitable excitation of the motor on the starting position is necessary. This most favourable value of the excitation is in the neighbourhood of the excitation for no-load at normal voltage and with $\cos\phi = 1$. By this the motor is over-excited on the starting step. Fig. 108 shows the value of the current surge arising with different degrees of excitation on switching over from "start" to "run" for an unloaded synchronous motor. It is very important that the switching over takes place with little or

no delay, so that during the process the motor remains as far as possible in synchronism with the supply. Even a comparatively small delay during switching over is sufficient to allow the rotating field to attain a considerable angular displacement. In the case of unloaded synchronous motors, this depends on the losses and on the flywheel effect of the rotor. If a synchronous motor must operate with a certain load torque even on the starting step, this fixes the amount of angular displacement, and this angular displacement in turn affects the size and duration of the ensuing current peak.

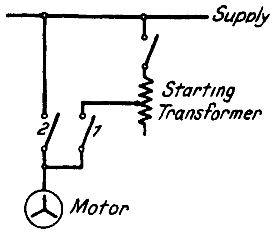


FIG. 109.
STARTING CONNECTION WITH SINGLE STEP STARTING TRANSFORMER

When *buffer choke coils*, as in Fig. 99, page 151, are used, only small switching-over peaks occur. In this case, the motor is thrown on the full voltage through a choke coil on the intermediate step with switches 1 and 2 open. After the switching current has died out, switch 2 may be closed on the full voltage. A few seconds interval on the intermediate step is necessary so that the current corresponding to the new voltage can settle down. With properly dimensioned choke coils, the machine can be switched on to full voltage almost entirely without current peaks.

If ohmic resistances are used instead of choke coils, so that the switching out of the starting transformer and the short-circuiting of the resistance can be spread over a few seconds, the motor during this interval runs on the full supply voltage with the resistance in series, and may begin to hunt or even fall out of step if there is a long interval and the resistance is unsuitable. When using ohmic resistances, it is therefore not desirable for the switching over to take more than a few seconds.

(*f*) SHORT CIRCUITS IN THE STARTING TRANSFORMER. Fig. 109 shows in principle the diagram of the starting connections of a synchronous motor or converter with a single-step starting transformer. Usually specially built starting switches are used for this, and the two pieces of apparatus, starting switch 1 and running switch 2, are so coupled mechanically that the first is switched out forcibly if the contacts of the latter are touching. The construction of the switch contacts is so arranged that the

switches cannot both simultaneously be closed, which might cause a short circuit of the starting transformer. The switches have also a buffer resistance to ensure switching over without current interruption, and to prevent short-circuiting of the whole transformer. This is so proportioned that no dangerous current peak arises in the transformer.

If, however, ordinary separate switches not mechanically coupled are used for starting and running switches, these must be electrically interlocked. If the interlocking is not done correctly, or if the auxiliary circuits are not properly arranged on the switches, a fault may arise in which the contacts of the full voltage switch are already touching before the contacts of the starting switch are opened, or even before the arc in this switch is broken. This causes a short circuit of the starting transformer. Such short circuit current peaks are responsible for forces which distort the winding and, if repeated, may cause a breakdown. In troubles of this kind, the first thing is to test the operation of the switch, and if necessary to improve this by shortening the contacts or by altering the arrangement so that simultaneous contact in the starting switch and the running switch is impossible. As already explained, the most certain method of preventing such trouble is a definite mechanical interlocking of the switches.

(*g*) Troubles Due to Starting Motors. Large synchronous motors which have to operate on no load as synchronous condensers or as machines to regulate the voltage by running with a wattless load, are chiefly started by special starting motors. Usually simple asynchronous motors or synchronous induction motors are used for this purpose. While the asynchronous motor generally has a smaller number of poles than the synchronous motor, a synchronous induction motor for this particular purpose has the same number of poles as the main synchronous machine. Asynchronous starting motors are usually adjusted to the correct synchronizing speed by rotor resistances, and the synchronous machine, after attaining the proper voltage and phase position, is then connected in parallel with the supply, just as an ordinary synchronous generator would be. When using a synchronous induction motor as a starting motor, the synchronous machine can be directly connected on to the supply without current peaks after the starting motor has been synchronized with the right polarity and the proper voltage attained. An important condition is that the

proper coupling position between the synchronous motor and the starting motor must be determined either at the manufacturer's works or during installation, and care must be taken that the coupling is bolted up as indicated by the supplier. The excitation of the starting motor and the synchronous motor should also be carried out with the polarity fixed from the beginning. If the polarity of either the starting motor exciter or the synchronous motor exciter has become reversed, that is to say, the positive and negative terminals changed over, the circuit cannot be closed, since supply voltage and motor voltage are in phase opposition and a dangerous short-circuit may occur. If the phase position is checked with a phase lamp or voltmeter and shows such an opposition, the exciter polarity of either the synchronous motor or the starting motor must be changed. A small phase displacement between the motor voltage and the supply voltage may also occur as a result of changed excitation of the starting motor. The proper exciter current strength should be fixed during testing at the manufacturer's works. or when the machine is installed.

CHAPTER XIII

TROUBLES IN D.C. MOTORS OPERATING EITHER SINGLY OR IN PARALLEL

1. Operation is Unstable. D.c. shunt wound motors should have a speed drop of between 2 per cent and 10 per cent of the no-load speed, from no-load to full load when the supply voltage is not altered. This value is affected on the one hand by the voltage drop in the armature circuit, that is to say, the increase in voltage drop with increasing load current tends to reduce the speed. On the other hand, the armature reaction effect, increasing with the armature current, weakens the resultant

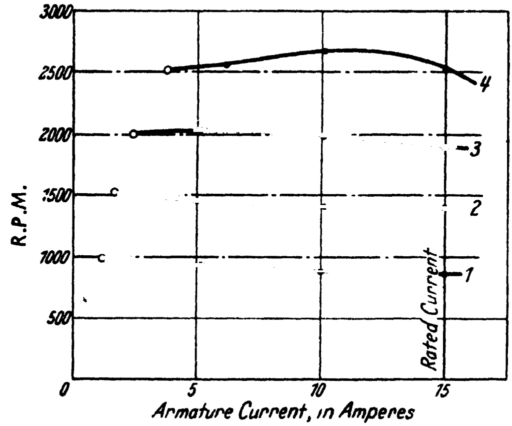


FIG. 110. SPEED OF A 6 kW. SHUNT WOUND MOTOR RELATIVE TO THE ARMATURE CURRENT AT RATED VOLTAGE 1 . . . 4 DECREASING EXCITATION

magnetic field and, consequently, the speed tends to increase. These two items thus have opposite effects. According to whether the first or second factor predominates, the speed drops or increases with the load. For example, in shunt motors with field weakening (for the purpose of speed control) at higher speeds and consequent lower saturation, the field weakening effect of the armature reaction may predominate, and the speed rise with increasing load.

The curves in Fig. 110 show the speed of a shunt motor of

6 kW. rated output relative to the load current with varying degrees of excitation of the shunt winding. It can be seen that with progressive weakening of the field, the influence of the armature reaction is greater, and on that account the speed drop between no-load and full load is smaller. If the field were weakened still further, an increase in speed might even occur with increasing load.

Many different kinds of motor drives require increasing torque with increasing speed. This requirement cannot always be fulfilled by a motor with an increasing speed characteristic since a stable drive is hardly possible. To ensure a stable drive, the speed must drop with increasing load, so that the curve of the load torque cuts the curve of the torque developed.

In shunt motors with interpoles, the speed can generally be regulated in ratios between 3 : 1 and 5 : 1 by field weakening. The upper limit is usually dependent to some extent on the commutation. If still further speed variation is required, the armature voltage of the motor, with the shunt excitation remaining the same, must be reduced by series resistances or by lowering the supply voltage. The latter method is used in the case of Ward-Leonard sets or with booster control. Often sufficient speed drop can only be produced by the insertion of a field strengthening auxiliary compound winding. By this a stable drive is ensured with increased field weakening. If such compounded motors are used for reversing service, it is necessary for the leads to the compound winding to be changed over at the same time that the direction of rotation is altered when changing the leads of the field winding.

If the operation of a shunt motor is unstable, in that its speed increases with increasing load, it may be impossible to adjust it to the required speeds. In this case, improvement may be effected by displacing the brushes out of the neutral zone.

Series wound motors, in which the load current produces the excitation, are characterized by high pull-out torque. While the speed of shunt motors only varies slightly with increasing load, with series motors it decreases rapidly. Fig. 111 shows the speed and torque curves of a series motor of 13 kW. output relative to the load current. If such a motor is unloaded during operation, its speed may increase to a dangerous degree. The speed regulation of such motors is generally done by means of series resistances in the main current circuit, often also in

conjunction with resistances in parallel with the field winding. The main sphere of application for such motors is for crane and traction service.

The compound motor, being a combination of the shunt and series type, also has similar characteristics which are nearer to those of a shunt or of a series motor, according to whether its shunt or series winding has most effect.

A compound motor, through the influence of the shunt winding, is protected against running away at no-load. When the

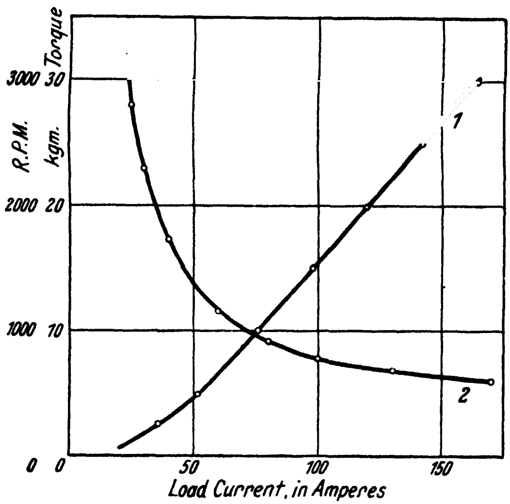


FIG. 111. TORQUE AND SPEED OF A 13 kW. SERIES WOUND MOTOR RELATIVE TO THE LOAD CURRENT
(1) Torque. (2) Speed.

compound winding is connected reversed—it should normally have a field strengthening effect—the speed and current of the motor increase very greatly with increasing load and stable operation is impossible. The method of determining the proper connection of the compound winding is outlined in Chapter XII, para. 2 (*g*).

2. Speed Regulation is Insufficient. The speed regulation in shunt and compound motors is in most cases carried out by varying the shunt field current. Decreasing the field current causes increase in speed, and vice versa.

Troubles in regulation may be of different kinds. Either the desired high speed is not attained, or else the speed remains

too high and cannot be reduced; or on certain steps there occur marked current peaks which operate the overload trips of the starter.

When the speed cannot be raised further and when there is not considerable overloading of the motor and too low voltage, it must be assumed that the field regulator is partially or wholly short-circuited. This fault may be due to the fact that single turns of the resistance coils or their end leads are actually in contact.

If the speed remains at its highest value and cannot be altered, the connection of the field winding leads must be wrong. If the connections from the field regulator back to the field coils are connected to the two terminals (1) and (3) Fig. 84, page 122, adjustment of the regulator arm produces no effect on the field current.

Heavy current peaks on certain positions of the field regulator suggest open-circuiting of the latter. Either the contacts of these steps are blackened and the contact brushes no longer make contact, or the connections to the studs have become loose. To prevent serious troubles due to breaks in the field circuit of a motor, the field regulators should be maintained in good condition. A break in the field circuit is the equivalent of a short circuit on the supply, and may result in the burning out of the motor. Short circuits between turns and layers of the field coils, or short circuit or reversed connection of a whole pole coil, may also cause trouble in the control.

Open-circuiting may arise in the regulating resistance as a result of blackened contacts, and the speed of the motor will drop when the faulty regulator position is reached. When there are short circuits in the resistance, regulation is ineffective on a few steps.

3. Current Fluctuations. Irregular fluctuations in the current, and as a result variations in the speed, may be caused by sudden changes in the load torque, for example, slipping of the transmission gear such as belts, ropes, or friction couplings.

In addition to these mechanical causes of trouble, there may be on the electrical side bad contacts in the exciter or the main field circuit of the motor, or faults in the brush-gear. Burnt contacts on field regulators, and insecurely fixed terminals on the connections to the field coils, often cause trouble. In such cases the current fluctuations may be so extensive as to trip the protective gear. If the commutation

of a d.c. motor is bad, it may in time cause damage to the running surfaces of the brushes as a result of excessive local wear. This is associated with extensive sparking, or may even cause the brushes to glow with resultant variations in current and speed. In this case the running surfaces of the brushes usually exhibit alternate sooty and polished streaks in the direction of the segments. This is termed *zone formation.* By rubbing over the commutator with pumice stone or a suitable carborundum stone with the brushes raised, this trouble can be temporarily cured, and the current fluctuations checked. The improved condition, however, will only last until the brushes have once more progressed to the same state. In trouble which can be traced to the above causes, current fluctuations of about $\pm$ 20 per cent of the rated current may be observed. A permanent cure can only be effected by improving the commutation. In Chapter V is described in detail the method of testing and adjusting the machine.

In the case of paper-machine drives, it may be observed that paper dust has collected under the brushes and the current is no longer being picked up properly, so that similar phenomena to the above appear.

4. Unequal Load Distribution with Parallel Operation. For certain drives, such as presses or dyeing machinery, it may be necessary at times for two or more motors to operate electrically and mechanically in parallel. The condition then arises that the individual motors must each carry portions of the load corresponding to their rated outputs. When this occurs the no-load speed and the speed variation between no load and full load of the motors must be the same. Equal speeds at no-load can be obtained either by balancing resistances in series with the field windings or by careful adjustment of the air gaps. If the motors are shunt controlled or provided with series control, the individual steps of the regulating resistances must be suitable for one another. The speed drops can generally be sufficiently precisely controlled by brush displacement.

5. Hunting. When individual d.c. generators and shunt motors with interpoles are working together, "hunting" of current and speed sometimes occurs. This begins with small fluctuations and within a short time becomes so marked that the switches trip out or the motor is inclined to race. This trouble occurs when the motor is unstable, that is, when its speed and torque increase simultaneously. It is specially likely

to arise when the motor is used for speed regulation by field weakening as described in a previous section. It may, however, also be due to brushes which are displaced backwards to a considerable extent, or which only lie on their trailing edges. To cure this, the brushes should be moved as far as necessary in the proper direction until the machine is stable. This will generally be when the speed drop between no-load and full load is about 2–5 per cent. If, however, the brushes cannot be displaced so far without spoiling the commutation, the best expedient is to insert a field strengthening series winding, say with 1–3 turns per pole. Such a winding can conveniently be made out of an easily obtainable insulated cable, if care is taken that successive poles are wound alternately left-handed and right-handed. The testing of a compound winding is outlined in Chapter XII, para. 2 (*g*).

CHAPTER XIV

TROUBLES IN ASYNCHRONOUS AND SYNCHRONOUS MOTORS OPERATING SINGLY OR IN PARALLEL

1. Current Variations in Asynchronous Motors. In addition to current variations due to the loading, asynchronous motors are also liable to variations in the stator current caused by the rotor. The causes include unsoldered winding ends on wound rotors, unsoldered connections between end rings and bars on squirrel-cage rotors, bad contacts in the short-circuiting gear, insufficient contact of the brushes of one slip-ring of motors having continuously-rated brushes. These current variations are generally associated with periodic vibrations and humming, of which the frequency becomes greater with increasing load and slip. At no-load the fluctuations are small and very slow. In squirrel-cage rotors with cast end rings, this trouble may occur without there being any apparent bad contacts. Only by cutting open the rings can joints which are very much oxidized be observed. To improve the condition the bad contacts must be re-soldered, although with cast end rings this is usually not practicable, and to remove the trouble the rotor must be entirely rewound.

Bad contacts on the short-circuiting gear are particularly common in dirty situations, for example, paper or cement works. The motors are often running under extremely severe conditions; all the motor parts become very dirty and the contact parts of short-circuiting devices have layers of dust. If these surfaces have, in addition, any grease adhering to them an insulating layer will form. The effective contact surface is therefore very much reduced, so that with continuous operation progressive heating spoils the contacts. This results in decreased contact pressure, increased heating and finally complete failure of the gear. Large accumulations of dust on contact surfaces may even lead to the open circuiting of the contacts solely as a result of their presence. When current variations are noticed on slip-ring motors, the contacts of the short-circuiting device should be tested, and all dirty contacts cleaned and where necessary replaced. The replacement of such contacts should be carried out with care.

Bad contacts may also occur on slip-rings when the brushes are sticking in the holders or are worn.

2. Load Distribution is Unequal on Asynchronous Motors Operating in Parallel. In drives with asynchronous squirrel-cage motors operating in parallel, the load may be unequally distributed if, for example, the belts are slipping or the ratios of the transmission gears do not correspond. An equal load distribution at all loads can only be attained with such machines when they have the same slip at normal operation. If they are very different from one another, equal load distribution can only be attained at one predetermined load where the transmission ratio of the pulley or gear is suitable.

In the case of asynchronous motors operating together with speed regulation by resistances in the rotor circuit, when the load distribution is unequal, either the resistances are incorrectly stepped or there is some fault in them, such as short circuits between adjacent resistance steps, or burnt contacts of the controller. If the stepping is wrong, the proper stepping is most simply determined by inserting temporary resistances and restepping the other resistances in accordance with the results obtained.

3. Hunting and Falling out of Step of Synchronous Motors. When a synchronous motor is suddenly unloaded, the rotating field, the position of which depends on the state of loading of the machine, takes up a new position corresponding to the no-load conditions, that is, it must be displaced in the direction of rotation. Because of the influence of the stator current and the rotating masses, its new state is not attained immediately, but a few oscillations to and fro occur which can usually be noted on the ammeter and wattmeter. As a result of the losses arising in the solid pole shoes or in the damper winding, these swings generally die out quickly.

Hunting may also be due to rapid changes in load or to load impulses, for example, in motor generators, when short circuits occur in the supply from the driven machines as well as short circuits in the feeding supply. In synchronous motors running on no-load for phase adjustment, hunting is always possible but most likely to occur when the machine has reverse excitation which is raised almost to the point at which the machine falls out of step.

In addition to these oscillations originating in the machines, forced oscillations caused by the driven apparatus may in some

cases occur when reciprocating machines are being driven by synchronous motors. The conditions are then the same as those already mentioned in Chapter X, para. 4 (*d*).

Synchronous motors may fall out of step with extensive voltage and frequency variations, such as may be caused by short circuits in the supply as well as mechanical overloading or wrong excitation. Generally, however, synchronous motors with salient poles which are loaded will remain in step if correctly excited, even with rapidly altering voltages. Falling out of step occurs sooner if, with voltage variation, there is simultaneous variation of frequency, particularly when a decrease in frequency is rapidly followed by an increase. The size of the masses to be accelerated and the load torque are of paramount importance as regards the behaviour of the motor. Unloaded synchronous motors with salient poles, working as phase shifters even when very much under-excited, will stand frequency and voltage variations of 10 per cent and over without falling out of step, while loaded synchronous motors with variations of this order will generally fall out of step and come to a standstill. Synchronous motors running on no-load will generally only slip back one pole pitch.

4. Excitation and Load Capacity of Synchronous Motors. The stronger the excitation applied to a synchronous motor, the greater the extent to which it can be overloaded. If the excitation is reduced and the output remains constant, when the state of under-excitation has reached a certain degree the motor falls out of step. The smaller the mechanical loading of the motor the greater is the degree of under-excitation which can occur before this ensues.

In Fig. 112 V-curves (stator current against excitation) are drawn for a synchronous motor with salient poles, 830 kW. rated output, for various constant loads. The values of the excitation at which the motor falls out of step are shown for each individual load. For example, it can be seen that at the necessary excitation for rated load and $\cos \phi = 1$ the motor can be loaded to about 50 per cent above the rated load before it falls out of step. Fig. 113 shows similar characteristic curves and pull-out points for a synchronous induction motor of 1 070 kW. rated output.

The curves 6 of Figs. 112 and 113 connect those points of minimum excitation for various loads below which the motor will fall out of step.

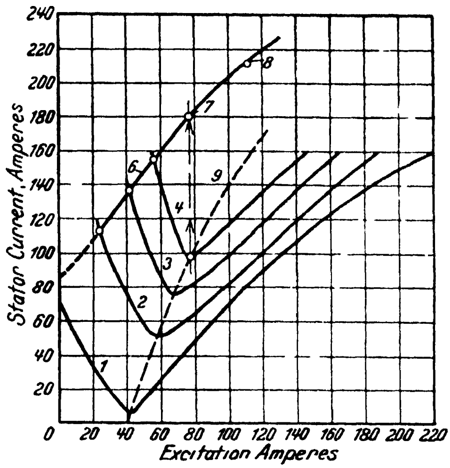


FIG. 112. V-CURVES FOR A SYNCHRONOUS MOTOR WITH SALIENT POLES FOR 830 kW RATED OUTPUT AT RATED VOLTAGE

(1) At no-load.
(2) At half load.
(3) Three-quarter load.
(4) Full load.
(6) Pull out points
(7) Pull out point for 6/4 rated load
(8) Pull out point for 7/4 rated load
(9) Excitation at unity power factor.

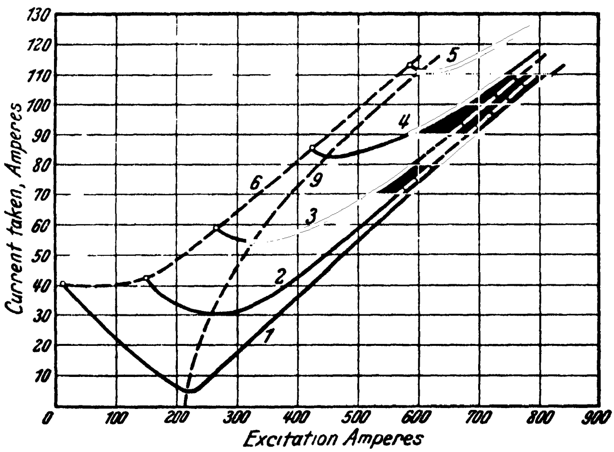


FIG. 113. V-CURVES OF A SYNCHRONOUS INDUCTION MOTOR FOR 1 070 kW. RATED LOAD AT RATED VOLTAGE

(1) At no-load.
(2) One-quarter load.
(3) Half load.
(4) Three-quarter load.
(5) Full load.
(6) Pull out points.
(9) Excitation at unity power factor.

Synchronous induction motors with cylindrical rotors on constant excitation will not stand such severe overloading as synchronous motors with salient poles. They have, however, the advantage that after falling out of step they will continue to run, and after the load has decreased will pull into step again.

When considerable load impulses are likely to occur on synchronous motor drives, for example, when driving wood-pulping machines in paper mills, it is to be recommended that the motor is always maintained in an over-excited condition. The limit of permissible over-excitation is, of course, determined by the heating. It is also desirable to equip the motors with suitable high-speed field regulators.

Over-excitation of synchronous motors is an expedient also employed to obtain power factor correction on supply systems.

In the case of synchronous motors operating on no-load as phase shifters, the excitation may be much reduced without the motor falling out of step. Phase shifters with salient poles will generally stand reverse excitation, and often pull out only when the "negative" excitation value is about 20 per cent of the excitation for $\cos \phi = 1$. If for such motors the excitation is slowly reduced to zero and increased again slowly in the opposite direction before the motor falls out of step, slow oscillations of the exciter ammeter can be observed, that is, the motor "hunts." At the excitation limit reached the motor slips, without either a large current peak, appreciable vibration or noise, into the new pole position for which the injected excitation is again positive. In this state the motor again runs satisfactorily but gives the wrong phase adjustment.

5. Load Distribution on Synchronous Motors Running Electrically and Mechanically in Parallel. When in very exceptional cases two synchronous motors are on the same supply and are also working on a single loading machine, the rotating fields must be exactly the same. Thus even when keying in position the rotating fields or couplings, this requirement must be kept in mind, and should it be necessary to remove the rotors for any reason, the halves of the coupling should be marked. Adjustment of excitation will only alter the distribution of the wattless load between the two machines. The same conditions may arise in the case of paralleled converter sets, consisting of synchronous motors and generators

which must run in parallel on the motor and generator sides. If the desired distribution of the kilowatt output is to be shared between such sets, the stator of one of the machines in each group must be arranged so that it will rotate through a few degrees.

CHAPTER XV

PROTECTION AGAINST FIRE AND EXTINGUISHING OF FIRE

To prevent as far as possible extensive burn-out of the windings of all machines, the original installation should incorporate protective apparatus, which, at the first appearance of a fault —i.e. a breakdown to earth or a short circuit—will disconnect the loaded machine from the supply, and cut off the excitation. These protective devices are dealt with in Chapter XXX.

If there is an arc in the machine, this may set fire to insulating materials. Since many winding parts, particularly end windings, are abundantly supplied with cooling air, the fire may spread even after the arc is extinguished. Burning, however, can be effectively stopped by adding a non-inflammable gas to the air supply. According to Stäger,* a modern fire-protection equipment must fulfil the following conditions—

(i) The oxygen content of the circulating air must be so decreased as to prevent further burning of the materials.

(ii) The quantity of oxygen available must be reduced so rapidly that only the damage immediately resulting from the particular failure occurs, and the material of the machine must not have time to be seriously burned.

(iii) The site of the burning must be cooled as rapidly as possible so that inflammable gas cannot be produced by organic insulating material. A temperature below that at which re-ignition will occur must be reached with all possible speed.

(iv) The oxygen content must be maintained low and the burnt place kept cool until there is no smouldering part left to light up again.

(v) The quenching medium must not be such as to damage the machine in any way.

Carbon dioxide and nitrogen are gases which fulfil these conditions and can be easily introduced into the cooling air systems of large generators.

In the type of closed cooling air system generally used to-day

* Stäger: *Elektrotechnische Isoliermaterialien,* 1931, pp. 122, 285 (in German). Also see Winfield: *Journal I.E.E.*, Vol. 81, p. 289.

for such large generators, the fresh air supply in case of fire can be quickly cut off. The dampers in the cooling air circuit are usually shut electromagnetically, simultaneously with the opening of the gas cylinders. The operation of the closing device is either done by protective relays or by push button.

For machines not having this protective gear, hand extinguishers must be used which throw the quenching medium in the form of powder, liquid, or foam on to the seat of the fire, and it is intended that they should provide a layer of gas excluding oxygen from round the burning object. These extinguishers should have the following properties—

1. Electrically non-conducting, so as not to be dangerous to the operator even at close range when live parts of the machine or set have to be extinguished.
2. Non-corrosive.
3. Free from materials which will permeate the insulation.
4. No tendency to produce poisonous gas or steam which would endanger the operator.

In electrical drives, the most common fluid extinguisher is composed of carbon tetrachloride, a jet of which is practically non-conducting electrically. This, however, has the great disadvantage that it forms poisonous phosgene gas and the user may be seriously affected. When employing this kind of extinguisher, particularly in confined spaces, it is advisable to proceed with the utmost care and to wear a gas mask. Another product of combustion is hydrochloric acid, and in addition the chemicals used in the holder of the extinguisher to provide sufficient pressure may act as electrolytes. All these electrolytes, particularly in conjunction with moisture, make the insulation into a conductor if they permeate the covering of the end windings. Very bad corrosion, particularly of the iron laminations, may also be caused in this way. Similar disadvantages are associated with all quenching media using electrolytes either for extinguishing or for producing pressure. In many cases, the damage done by the extinguisher is far more serious than that caused by the fire itself, and the whole winding must be re-insulated and the laminated core reconstructed.

Certain fire extinguishers of the foam or snow producing type which contain carbon dioxide do not have these objectionable characteristics. They do, however, produce too small a jet, so that it is sometimes not possible to cover the burning

place effectively in cases where one cannot get very near to the machine. In addition the jet is a conductor at least as long as it retains its form.

Water is, of course, an excellent fire extinguisher, but in electrical plants where there are live parts its use is too dangerous to the workpeople, as it may conduct current to the extinguisher. The damage to the insulation by water is small, and in any case, with proper care the machine can be successfully dried out. Iron parts may possibly rust, but the danger to the machine is very small if drying by hot air is carried out as rapidly as possible. In machines already warm from running, rusting is practically impossible.

For extinguishing oil fires, "foam" and "snow" extinguishers are most used. Water must not be sprayed on to burning oil since the two combine to produce an explosive mixture of hydrogen and oxygen, and large flames result. Water can only be usefully employed to reduce the temperature of the iron parts adjacent to the site of the burning transformer tanks and the like, and to prevent further heat being conducted to the oil.

CHAPTER XVI

CLEANING AND MAINTENANCE OF MACHINES

THE cleaning and maintenance of individual machine parts has already been described in connection with the troubles associated with these parts, so that it is superfluous to repeat the information. The frequency of the periodical overhaul or complete reconditioning of machines depends on the service and the surrounding conditions. Frequent cleaning is chiefly necessary for machines in very dirty situations such as wood working factories, rolling mills, conveying plants, and chemical works. Coal and iron dust, oil and chemical vapours are particularly harmful. Chapter XXXIX, para. 4, gives more detailed notes on cleaning dirty windings. It is obvious that careful cleaning and maintenance of machines will prevent many failures. It should always be the aim to prevent rather than cure defects. Amongst the measures which can be taken to prevent trouble can be counted all protective devices against excessive voltages or currents, which limit the damage at an early stage by cutting the machine off from the supply and cutting out the excitation, and also built-in fire extinguishing devices as used on modern generators. The proper choice and use of protective devices for electrical machines is discussed in several paragraphs of Part III of this book (Auxiliary Apparatus).

PART II

TRANSFORMERS

CHAPTER XVII

OVERHEATING

OVERHEATING of a transformer is as serious as fever in a human being. In the latter case, however, the feverish condition can be referred to a fixed normal temperature, whereas in the case of a transformer it is not so simple to define. Its normal temperature is variable and dependent on its load, and the temperature and quantity of the cooling medium. It is necessary to know the temperature at which the transformer normally operates, having regard to the given conditions, before the degree of overheating can be determined by using a thermometer.

1. Permissible Temperature Rise of Transformers. It is simpler to consider in the following paragraphs not the actual temperature but the temperature rise, that is, the difference between the temperature of a transformer part and of the cooling medium.

(*a*) OIL-IMMERSED TRANSFORMERS. Here we can limit ourselves entirely to the question of oil heating. All losses due to any defect are conducted away by the oil. Only a very small proportion of large transformers are provided with devices which indicate the temperature rise of individual parts of the transformer during operation.

According to B.S.I. Specifications, the increase of temperature of the oil in a transformer should not exceed 50° C. This is on the assumption that the temperature of the cooling medium when air cooling is employed does not exceed 35° C., and for water cooling 25° C. Many transformers, however, are so dimensioned that the temperature rise of the oil at full load is less than 50°, in view of the temperature drop between winding and oil, or to permit a higher temperature for the cooling medium on entry. The correct value for the temperature rise for normal methods of cooling is always given by the supplier. Since, however, the transformer is not always

fully loaded, the proper temperature for other load conditions ought to be known. For many transformers, the daily load, and consequently the heating, have a periodic curve. Those in charge of the apparatus are therefore well advised to plot such a curve for it soon after its installation, showing for the characteristic load curve the heating, and the corresponding oil and cooling medium temperatures. This immediately gives a practicable standard of reference for the transformer.

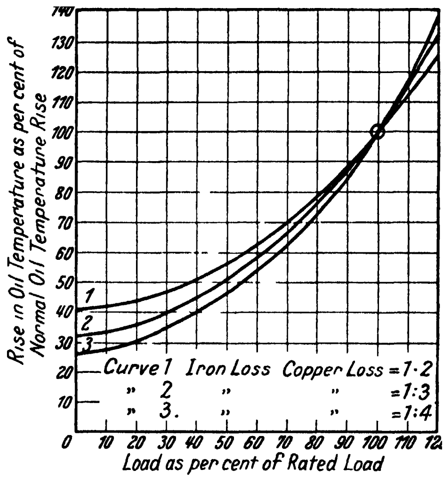


FIG. 114. RISE IN OIL TEMPERATURE FOR DIFFERENT LOADS

A further reference for heating with steady loading is provided by a curve, as in Fig. 114, showing oil heating in relation to the steady load. It must, however, be remembered that when the load is changed, the oil temperature only alters slowly. In most transformers with ordinary cooling 8 to 10 hours, or for water cooling 5 to 7 hours elapse after a change in load, before the heating and loading can be directly compared as in the curve.

(*b*) AIR-COOLED TRANSFORMERS. In these the temperature rise of the impregnated winding should not exceed 60° C. according to B.S.I. standards. Except where the heating of the windings can be determined by built-in thermostats or the like, which can rarely be done and is only possible for large transformers, the temperature rise of the cooling air must be

observed. In the case of natural cooling, however, the air quantity can be greatly altered by wind, open or closed doors or windows. The rise in air temperature is inversely proportional to the quantity of air, so that measurement of the heating of the air is a very uncertain method of checking the state of the transformer. Only in uniformly ventilated transformer rooms and with accurate observation of the conditions over the whole air path is this method practicable.

2. Abnormal Temperature Rise of Transformers. If abnormal heating occurs, the cause should first be sought outside the transformer. It is possible that the supply of cooling medium is insufficient. With natural cooling a flow of fresh air of about 175 ft.^{3} per kW. loss per min. is usually adequate.* With this air quantity, the rise in air temperature is about 10° C. With smaller air quantities the rise is greater and the average cooling air temperature is greater. Also as a result of the lower speed of flow the temperature drop at the surface of the transformer increases. Care should be taken that the air flow is not being spoilt by obstructions or because the inlet or outlet openings are partially blocked up.

With forced air cooling by fans, an air quantity of about 175 ft.^{3} per min. per kW. loss is also generally employed. The cross-section of the air current is in this case artificially narrowed along the length of the transformer so as to make the speed of the cooling air as great as possible over those transformer parts to be cooled. The heating of the transformer is then largely dependent on the air quantity. When overheating occurs, the first thing is to ascertain if the fan is working at normal speed or if there is any obstruction in the air channel. The air supply per minute should also be measured with an anemometer. The measurement is best taken some way down the inlet duct on the suction side of the fan, and on different parts of the cross-section so that a correct average may be obtained for the air speed.

In transformers with water cooling with or without artificial oil circulation, the usual cooling water quantity is about 0·22 gal. per min. for 1 kW. loss and the temperature rise of the water should be about 15° C. If the water quantity were halved, its temperature rise would increase to about 30° C.

* For information on the ventilation of transformer rooms, see: *E.T.Z.*, 1929, p. 1623 (F. Sieber and F. Heiles).

The average temperature in the cooler would then be 15° C. over the inlet temperature compared with 7·5° C. for normal water supply. The rise in the transformer oil temperature would increase due to this difference of 7·5° C., together with a small additional amount as a result of the decreased heat transfer from the cooling tubes to the water on account of the lower rate of flow. The increase in oil temperature, however, is comparatively small, and in fact, a decrease in the water supply of between 10 and 20 per cent does not appreciably affect it. The signalling device on the water flow meter can on this account be so fixed that these variations do not give the alarm. If considerable overheating has not led to any movement of the water quantity indicator, insufficiency of cooling water is probably not the cause. Other defects, perhaps in the transformer itself, are more likely.

When insufficiency of cooling water has once been found to be the cause of overheating, the means adopted to cure the trouble should always be noted down.

It was assumed to start with that the effective load of individual transformers can be determined precisely. If on the other hand, the load distribution to single units is wrong, it may be that a transformer working in parallel has been carelessly connected on to a different tapping from the remaining transformers and overloading has thus developed. This may easily arise when tapping switches permit the terminals to be conveniently changed. Those cases are omitted here in which parallel operation has been wrong from the start due to wrong dimensioning of the transformer or of the connections.

A very distorted voltage or current wave of which the cause is outside the transformer may also cause overheating. A pronounced third harmonic in the voltage wave in the case of a transformer not having a delta-connected winding may easily cause certain parts of the oil tank to carry a leakage flux. In such cases some inequality of the heating of the surface of the tank is usually noticeable.

3. Abnormal Heating of Faulty Transformers. If an abnormal temperature rise occurs without there being any apparent cause external to the transformer, such as are mentioned above, something must be amiss with either the transformer or its cooler. The transformer should be taken out of service, and if this is done at an early stage, the trouble will generally

have only affected one part of the apparatus. The many faults which may arise are grouped in the following sections according to the parts of the transformer in which they occur. In the first place a few electrical defects are discussed which apply to the transformer as a whole.

CHAPTER XVIII

GENERAL ELECTRICAL TROUBLES

It is very important when designing a transformer that the voltage conditions of the plant on which it is to work should be exactly known. Cables, type of switchgear, voltage drop, even when it is not intended that the machine shall work in parallel, must be carefully determined. If, for example, the supply in an installation is in practice above the rated voltage, the magnetizing current may become excessive. There is nothing to be done in this case except to see that the transformer is adequately designed for the highest probable voltages.

In this connection, the current surge on switching in should also be considered as it may become dangerous, particularly when too high a working voltage exists. The fuses used as protective devices on small transformers may burn out if the voltage is switched in accidentally at the instant of passing through zero. A buffer resistance may be used on the switch for protection against this comparatively rare occurrence.

Unsymmetrical loads as, for example, in the case of lighting transformers, may cause marked inequalities in the phase voltages, and additional losses in different parts of the transformer unless suitable switchgear is chosen to prevent it. The well-known zigzag connection on the secondary side or delta connection on the primary side tends to bring about equalizing. Unsymmetrical voltages may also occur on individual phases due to the tap-changing mentioned above, and as a result of open circuiting between connections, also from bad contacts.

If a three-phase group is formed from three single-phase transformers, one side must be connected in delta, since otherwise the wave shape of the phase voltage is greatly distorted. With star connection without a primary neutral conductor, the sum of the instantaneous values of the three magnetizing currents should always be zero (Kirchhoff's rule). For a sine wave of voltage, the normal magnetizing currents do not, however, fulfil this condition. In Fig. 115 the magnetizing currents I_0', I_0'', I_0''' are drawn in their appropriate phase positions for a comparatively small flux density. At the

current maximum of I_0' there only occur in the two other phases the two small instantaneous values i_0'' and i_0'''. The sum of the magnetizing currents i_0'' and i_0''' is much smaller than the magnetizing current i_0'. Since now in the three single-phase cores the fluxes can form independently of one another, they adjust themselves so that the rule stated for magnetizing currents is adhered to, and the wave shapes of the phase voltages become non-sinusoidal.

The same phenomena occur also in the case of three-phase shell type transformers and five-legged core type transformers, where the phase fields are likewise independent of one another. The resulting very marked distortion of the secondary phase voltage wave is obviously not permissible. Delta connection of the primary or secondary windings facilitates the internal equalizing of the magnetizing currents. If it is not practicable to connect one of the two windings in delta, a third winding must be provided.

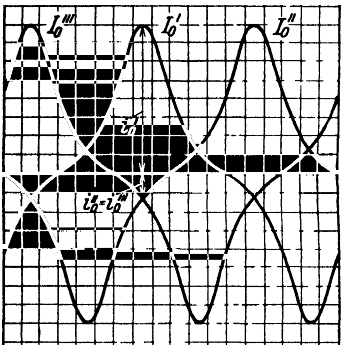


FIG. 115. MAGNETIZING CURRENTS OF THE THREE PHASES FOR A SINE-WAVE OF VOLTAGE

The voltage drop is fixed by the design of the transformer. The desire to keep it as low as possible led in the early days of transformer construction to designs with very low short-circuit voltages. The growth of power station loads resulted in a great increase in size of the short-circuit currents, and weak parts of the plant developed faults. Since then a compromise has been reached as regards choice of short-circuit voltages, between the desire to have as low a voltage drop as possible between no-load and full load, and the demand for a strictly limited short-circuit current. To-day the short-circuit voltages usually lie between 4 and 5 per cent for small outputs and 10 and 12 per cent for large outputs. In plants with old transformers with too small short-circuit voltage, choke coils without iron cores are inserted to limit the short-circuit currents. Choke coils with iron cores of the usual proportions become saturated at less than twice normal current and so cannot absorb any large portion of the voltage with further increase in current.

They will, on this account, only limit the short-circuit current to quite a small extent.

For successful parallel operation it is well known that the cables, switchgear and short-circuit voltages of the units in parallel must correspond exactly. Differences between the maximum and minimum short-circuit voltage up to about 33 per cent can be balanced by a suitable alteration of the transformation ratio, so that at full load and for a fixed value of cos ϕ the load distribution is correct. Too low short-circuit voltages can also be raised to any desired value by the introduction of choke coils. For parallel operation choke coils with iron cores, which are cheaper than current limiting choke coils without iron cores, will suffice.

To measure the transformation ratio, the transformer should be supplied on the high- or the low-tension side, whichever is most convenient. By means of two voltmeters, either connected directly, or, in the case of high voltages, through potential transformers, read by two persons simultaneously at a given signal, the high and low voltages may be ascertained. For transformers with very high voltage, if no suitable potential transformer is available, a fraction for example, one-fifth to one-tenth of the rated value can be used for measuring. If there is no voltage source available that can be regulated, the measurement in many cases can be carried out with the transformer connected on its high voltage side to the low voltage bus-bar. For polyphase transformers, however, the voltages of both sides must be measured either between two corresponding terminals or between the same phase terminals and the star point. With star zigzag connection, the voltage of the zigzag leg (i.e. the voltage between terminal and neutral point) should be compared with a corresponding voltage of the star leg, so that the compared primary and secondary voltages are composed of partial voltages of two similar groups.

For determining the polarity of a transformer, the primary winding must be supplied with low voltage, one terminal of this winding having previously been connected to a terminal of the secondary winding. The potential differences are then measured between alternate terminals of the two windings, and the values compared with those determined from a voltage diagram drawn to scale.

Before transformers are connected in parallel, the following procedure should be adopted (Fig. 116).

The transformers to be paralleled are connected on the primary side exactly similarly—that is, terminals of the same sign are connected with the bus-bar *R*, and the same for the *S* and *T* bus-bars. On the secondary side, two terminals of the same sign, i.e. *v-v* (see Fig. 116) are solidly coupled together and the voltage between the remaining like terminals is measured. Only when this is zero can the transformers be connected in parallel. The measuring range of the voltmeter

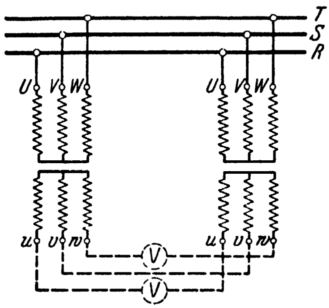


FIG. 116. VOLTAGE CHECKING BEFORE THE PARALLEL CONNECTION OF TRANSFORMERS

must be sufficiently large to deal with twice the secondary voltage.

If the voltage difference measured between two like terminals as described above, when determined with a voltmeter of small measuring range, amounts to a fraction of the voltage of one of the transformers, then the cable arrangement is probably wrong. When the transformers are equipped with tappings, they may have been connected on the wrong tapping and the fault can be quickly cured.

When on the other hand, the voltage between two like terminals is either equal to or greater than the voltage of one transformer, the phases are not balanced. There are, then, either wrong connections of the terminals or reversed connections inside the transformer. The method of determining the polarity described above also helps to determine the type of reversed connection.

CHAPTER XIX

TYPES OF PROTECTION

ABNORMAL conditions arising in service must be cured as quickly as possible. Although it is not always possible to prevent troubles occurring in transformers, their effect can at least be limited by suitable means. Apart from devices which indicate at once the appearance of abnormal conditions, apparatus is used which operates either to prevent the damage entirely or to stop it spreading. Overheating can be brought to the notice of the maintenance staff by means of a light or sound signal operated by a contact which is closed when the outlet temperature of the air or oil exceeds a certain permissible value. Switching out can easily be arranged to take place simultaneously by means of another contact.

For measuring winding and iron core temperatures, measuring devices are used having built-in thermal elements connected to recording instruments on the switchboard. The price of these devices is rather high, particularly when a high winding voltage necessitates the intermediate connection of an elaborate insulating transformer. They are, therefore, only used in the case of very large transformers. The connections between the thermal element embedded in the winding and the insulating transformer form a source of danger that must be kept in mind, and direct measurement of the winding temperature is desirable.

In addition, the usual overload protection should be employed to protect the transformer from overloads, although this generally only operates when the defect in the inside of the transformer is already extensive. The fault current must in this case exceed the maximum load current.

The demand for selectivity of the protective gear, which is desirable in large installations, that is to say, the characteristic ensuring that only the faulty part of the apparatus is cut out, has led to the use of the differential protective device. This balances the primary and secondary current in each phase. The transformation ratio of the transformer is dealt with by current transformers. In the case of a defect, the ratio of the currents is altered by the fault current produced which flows through the relay and thereupon switches out the transformer.

The sensitivity of the relay, however, must be limited for the following reason. The magnetizing current of the transformer, according to the voltage and load, alters the transformation ratio of the currents. Also the series transformers used generally have different voltage characteristics, and when transient short circuits occur there may be differences in the

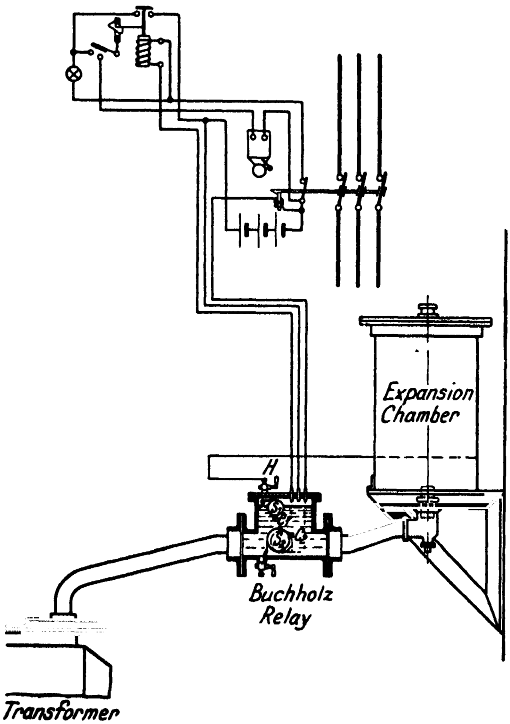


FIG. 117. BUCHHOLZ RELAY

secondary currents of the series transformers which cause the main transformer to be switched out unnecessarily. The differential relay may, on this account, only be used in connection with fault currents which are greater than the maximum possible value of the magnetizing current, or than the maximum difference of the fault currents in the series transformer for transient short circuits. In addition, the differential relay must generally operate with a slight time lag to allow for the current surge on switching in the transformer. To balance the

variable transformation ratio of transformers which can be regulated and which have a large range of tappings, there must be provided in the relay circuit either series transformer tappings or an adjustable auxiliary transformer

The complicated structure and appreciable cost of differential relays have limited their application very considerably.

Recently another type of protection for oil-immersed transformers has found great favour, operating by means of a chemical reaction such as decomposition of the insulating material caused by the fault current or by overheating. This is known as the *Buchholz relay* after its inventor. Fig. 117 shows diagrammatically the whole protective system. It is an improvement on the differential relay in that more kinds of faults are detected and the device is simpler in construction. The gases emitted as a result of even the smallest defect or with too much heating of the insulation collect in the Buchholz apparatus (Fig. 117) until the float S_1 is pressed down sufficiently to close the alarm contact C_1. When, on the other hand, there is a serious defect producing large bubbles of gas, the float S_2 comes into play and switches out the transformer by means of the contact C_2. It may happen that after a transformer has been put into service, air may collect in the apparatus. In this case, the maintenance staff should remove it through the tap H.

The surest protection for a transformer is, however, a carefully planned design in conjunction with perfect construction. Experience shows that with such transformers no trouble is likely to arise in service for at least a decade.

CHAPTER XX

TROUBLES IN INDIVIDUAL PARTS OF THE ELECTRICAL CIRCUIT

1. Windings. Winding defects are most frequently caused by damage to the wire and coil insulation resulting in the short-circuiting of a greater or smaller part of the whole winding. If a transformer is equipped with the Buchholz protective device (Fig. 118) the warning signal is operated due to the development of gas, and the transformer is cut out at an early stage in the trouble. A sensitive differential relay will operate when about 0·5 per cent of the number of turns of a winding are short-circuited. The usual excess-current relay, however, does not operate until quite a large part of the winding is short-circuited and consequently, as a rule, extensive damage has already been done. The production of smoke or noise from the interior of the transformer may occur long before the relay operates. Fig. 119 shows the extent to which a winding may be damaged before the transformer is cut out by the relay. In the case of this transformer, the current setting for tripping out had always to be kept unusually high to ensure continuity of supply. The development of such a defect may take several days or weeks, since the short circuits may temporarily become open-circuited due to melting of the copper. As a result of excessive heating and the action of molten copper particles, the wire and coil insulation adjacent to the site of the short circuit becomes permanently damaged, and finally the transient excess voltages, produced by making and breaking of the arc, cause a flash-over. Consequently a fault originally of small extent may burn the whole winding along one leg of the transformer.

Fig. 120 shows another phenomenon—the formation of a "nest" on the low voltage winding of a furnace transformer. These windings were bare on account of the low voltage and merely insulated from one another by being spaced and immersed in oil. The low winding voltage and the oil circulation tended to prevent the spread of the trouble, but at the site of the short circuit a "nest" of oil mixed with carbon dust accumulated. When analysed chemically, it was found to

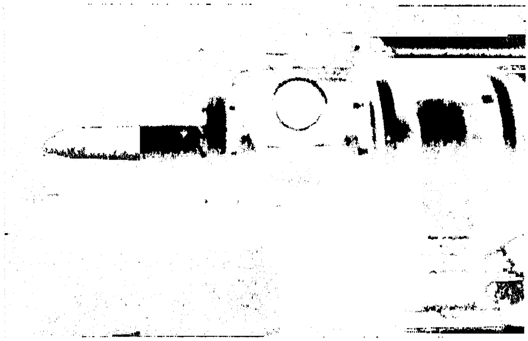


FIG. 118. BUCHHOLZ APPARATUS MOUNTED IN POSITION

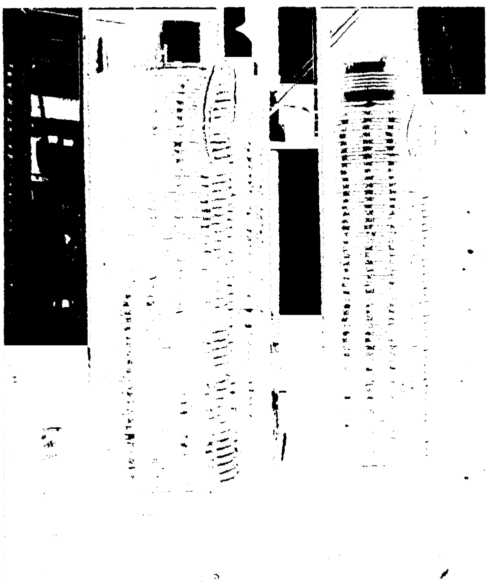


FIG. 119. EXTENSIVE DAMAGE OF A TRANSFORMER WINDING DUE TO SHORT CIRCUITS BETWEEN TURNS

contain actually 95·8 per cent carbon and only 1·5 per cent copper. Fig. 121 shows the damage under the "nest." The defect is marked at *f* and consists of a short circuit between the two sections of one coil lying adjacent to one another. All coils were parallel connected so that there was no voltage difference between adjacent coils. In the case of this transformer, during a long period the maintenance man noticed leaking oil vapour, as though oil were being boiled out. Since, however, no smoke could be detected as a sign of burnt insulation material, the

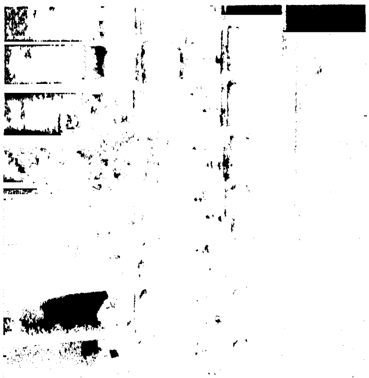


Fig. 120. Short Circuit between Turns on an Oil immersed Transformer Winding
"Nest" of burnt oil

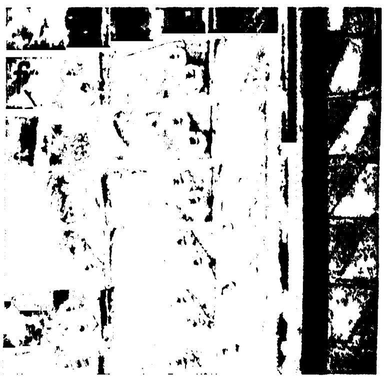


Fig. 121 Damage to the Copper Conductors under the "Nest"

transformer was allowed to continue in service until it was convenient to overhaul it.

In this and all similar cases, actual ignition of oil is not likely since air is excluded from the arc or the heated place. It is often possible to determine the winding phase in which the defect occurs before dismantling the transformer, by measuring the transformation ratio of each phase.

The causes leading to winding defects cannot always be clearly determined, but in many cases deterioration of the wire insulation by overheating due to overloading, or short circuits which have been cut out too late, are responsible. Overheating may also arise without there being any overloading, particularly when there are large accumulations of sludge. Inferior grades of oil containing acid are a further cause of damage to the wire insulation and may lead to serious defects.

Moisture in the windings or in the oil is another source of trouble. Very often an examination of the oil in the transformer will provide a clue to the cause of the breakdown (Chapter XXXIX, para. 5, deals with this point).

Foreign bodies such as pieces of wire, nuts, washers, or drops of solder which have been carelessly left in the windings during either installation or overhaul are sometimes responsible for faults. A particularly large over-voltage may ruin a winding that was previously in perfect order. The effect of a lightning stroke on the transmission lines in the immediate neighbourhood of the transformer may damage the windings, even though protective gear is provided. On the other hand, excessive voltages due to breakdowns to earth of the leads and also in the switchgear will not affect a good transformer winding, except in cases where marked resonance increases the voltages on the transformer.

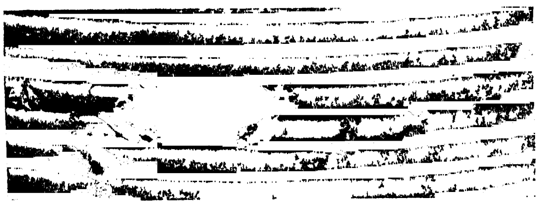


FIG. 122. SHORT CIRCUIT BETWEEN TURNS ON A SINGLE LAYER COIL

A further group of causes of trouble consists of mechanical irregularities in the construction of the winding which lead to damage of the wire or coil insulation. A winding which is insufficiently clamped may move at each short circuit or heavy overload, and after the short circuit spring back to its original position. This movement in the winding will almost certainly cause direct damage by abrasion. Often the movement increases with time, and after many short circuits causes appreciable displacement of the distance pieces.

Fig. 123 shows a transformer which was subjected to arduous conditions with many short circuits, in which the winding was insufficiently clamped. On the left hand, where the sections are still complete, three projecting pressboard strips can be seen at the top which have been forced up by the pressure from repeated movement on short circuits. These strips, used as

distance pieces between the inside of the winding and the insulating tube, have moved 30 in. On the inner winding, consisting of wire wound edgewise on a tube, the distance pieces between the sections have become much displaced (see middle phase in illustration). It is obvious that windings which have become as loose as this will break down after a few further current surges, and a short circuit will probably develop.

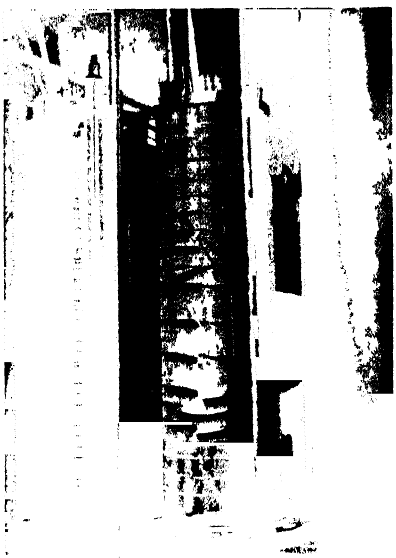


FIG. 123 DISPLACEMENT OF INSULATION DUE TO MOVEMENT ON REPEATED SHORT CIRCUITS

Air-cooled transformers are subject to similar troubles, with the exception of those arising in connection with oil. There is also an additional potential source of trouble in that they may be fouled by dirty cooling air. In particular, "dead" pockets, that is, places where there is no through draught, cannot always be avoided and may accumulate dust and cause local overheating

Winding defects should always be repaired either by the manufacturer or by workmen with experience of the job. Large transformers, particularly for heavy currents, can only be successfully repaired by workers thoroughly familiar with their construction. Careful supervision of the apparatus will to a great extent prevent winding defects arising. The transformer should not be allowed to reach too high a temperature, and overload protective gear and cooling plant should be kept in order. From time to time, perhaps once a year, the oil should be tested as regards moisture content, change in colour, or accumulation of sludge. (See Chapter XXXIX, para. 5.) When an oil testing plant is available, the breakdown value of the oil should be tested on various samples. Transformer oil with at least 40 kV. breakdown value between the usual

electrodes (caps as specified in R.E.T. 1930 or balls of 12·5 mm. diameter), 5 mm. apart is, however, sufficiently good for almost all transformers. Standard British tests for transformer oil are given in B.S.S. 148, and are very similar to these. If the electrical strength is less, the oil should be cleaned or renewed. (See Chapter XXXIX, para. 5.)

Air-cooled transformers should be protected against the ingress of dirt with the cooling air, and where necessary filters should be provided.

It is recommended that transformers subject to severe mechanical stress—for example, frequent short circuits—be lifted out of the tanks every two or three years as a precautionary measure. The windings should always be adequately clamped, and if necessary the clamping devices should be tightened. The coil connections should also be examined for signs of loosening.

During any repairs or overhauls necessitating alterations to the transformer, no screws, keys, bolts, washers or any other metal objects should be laid down on the transformer, as they may be accidentally knocked into the winding.

The protection of transformers against excessive voltages is a problem not yet fully solved, but it does not come within the scope of this book. Modern transformer construction, however, has advanced so far that excessive voltages likely to arise in service can almost always be dealt with by adequate insulation of the winding.

2. Outer Winding Insulation. By outer winding insulation is meant those parts insulating one winding from the other or from other parts of the transformer. It includes also spaces between the windings more or less filled with layers of press-paper or pressboard, and the distance pieces between end windings and yokes. A break through any of this insulation is the equivalent of a breakdown to earth of the winding in question. It is usually followed immediately by a breakdown between turns due either to the local effect of the arc or to the transient voltage caused by the breakdown of the insulation. The external phenomena are in this case the same as those described in the previous section. The Buchholz protective device should already have operated as the result of a pure breakdown to earth, while the differential or ordinary excess current protective gear will be tripped when the short circuit appears. The insulation tester does not always show the

resultant breakdown, particularly when applied to a heavy layer of insulation. The insulation resistance may remain large practically indefinitely, since the insulation due to oil or air spaces will always renew itself, and there are cases in which a breakdown to earth does not immediately put the transformer out of action. It may continue to operate, but the break-

FIG. 124. TRACKS LEFT BY CREEPAGE CURRENTS ON THE SURFACE OF AN INSULATING CYLINDER

down will recur with the next small excess voltage. If the breakdown is towards the inside, a short damped crackling can usually be heard. If it is towards the tank, it causes a lighter, sharper sound, and in each case it is only a question of time before a short circuit between turns occurs.

These defects of the outer insulation, which are extremely unusual in properly constructed transformers, are frequently caused by damp, inferior oil, dirt or foreign bodies. The outer

winding insulation will generally withstand safely excessive voltages of short duration, up to the magnitude of the approximate flash-over voltage of the terminals. The time lag in the breakdown of solid insulating materials and oil has an advantage in such cases.

Defects in the outer winding insulation on low-voltage transformers can often be repaired on site by competent personnel. When damp, inferior oil or dust is the cause of the trouble, it is simply a matter of replacing defective insulating tubes, washers, or end distance rings by new ones, and doing the necessary drying and cleaning.

Insulating pieces adjacent to the path of the breakdown often exhibit tracking due to stray currents, as shown in Fig. 124. These, however, generally only affect quite a thin surface layer of the material and can be scraped off. The site of the damage to the winding should be repaired by careful renewal of the wire insulation, and particular attention should then be given to cleaning and drying. Instructions as regards drying are issued by all manufacturers for all types of transformers. For heavy current transformers, it is advisable to apply to the manufacturers to carry out repairs, particularly when the cause of trouble has not been ascertained with certainty.

To prevent the insulation defects mentioned, the same precautions are effective as those described in the previous chapter for the prevention of winding defects.

3. Connections. By connections are meant all conductors between the various winding parts and between winding parts and terminals. Connector defects may occur as breakdowns to earth, in the form of breakdowns to either the tank, the iron frame or other earthed constructional parts. The symptoms are the same as for a winding breakdown to earth. If the breakdown current is so small that the protective gear is not tripped, an arc to earth may exist for a long time, until it causes either a winding short circuit or until a hole is burnt in the tank and the oil leaks. The latter is, however, of rare occurrence.

The other type of connector defect, that is, breakdown between two adjacent connectors or between a connector and the winding, naturally becomes apparent as a winding short circuit.

The principal causes of these connector defects are damp, inferior oil, dirt, and foreign bodies. In addition, as a result

of too low an oil level, parts of the connectors may project above the oil level, and flash-overs occur in the air between the adjacent parts or between them and earthed parts. In badly constructed transformers having the connections insufficiently supported, these may be bent by short-circuit forces and pressed either against one another or against other parts. This is particularly likely in the case of oil-immersed transformers with bare low voltage connectors, unless the connector bars are held apart at frequent intervals by distance pieces.

Insufficiently supported connectors may sometimes be broken by vibration arising on long railway or lorry journeys. Transformers for traction service should obviously have the connections very firmly supported.

When live parts are carelessly withdrawn from or replaced in the oil tanks, the connector insulation may be damaged by scraping on the edges or on welded seams.

Connector defects can generally be repaired on site by competent workmen. The table below will serve as a guide to the amount of insulation necessary on the connectors of oil-immersed transformers—

Working Voltage (kV.)	Approximate Radial Thickness of the Connector Insulation (in.)	Approximate Additional Distance through Oil (in.)
6	0·06	0·40
10	0·08	0·60
20	0·12	1·00
35	0·20	1·60
50	0·27	2·00
70	0·40	2·75

Note.—The thicknesses given for connector insulation refer to pressboard, presspaper, or insulating paper wrapped by hand on the conductor.

For heavy currents and in the case of air-cooled transformers, the distances are almost entirely dependent on the design, and the supplier of the transformer should be consulted.

Connector defects in transformers can be prevented by the same expedients used to prevent winding troubles. Adequate support of connectors to prevent their movement, and the locking of all fixing screws may be particularly mentioned.

4. Bushings. In discussing these, it is necessary to distinguish between flashing-over and puncture. A flash-over of brief duration generally causes little or no damage to the bushing. Porcelain terminals, particularly the larger ones with guards, may exhibit burning marks on the surface of the flanges as the sole effect. Bakelized paper terminals may show local burning on the insulation, but this is generally only superficial. The quality of the insulation is so little reduced that it will withstand the normal voltages arising in service, and only further excessive voltages will lead to subsequent flash-overs. Flash-overs between two adjacent terminals will cause greater or less signs of burning on the terminal leads according to the kVA. in the short circuit. On adequately designed condenser bushings with sufficient means for conducting away heat, direct punctures through a sound bushing hardly ever occur except with bad workmanship. Badly constructed bushings will usually explode if a puncture occurs (Fig. 125). If condenser-type bushings are insufficiently dried before use, they are liable to puncture, and a puncture will also occur if, from mechanical causes or due to excessive heating, cracks form in the insulator body. The normal temperature variations due to load fluctuations or atmospheric disturbances will, however, have no effect on designs of terminals usual to-day.

In addition to damage to the insulator from mechanical causes or by overheating, which are generally the result of careless erection or of some defect in the transformer, reference must be made to the damage caused by the use of unsuitable cement on the flanges (see Chapter XXXIX, para. 3). Experience has shown that this never occurs with a good cement. Deterioration of the oil in oil-filled terminals is unlikely to progress to such an extent as to cause a puncture. Even when there is leakage because the under side of the terminal connection has become dirty, a modern insulated bushing has sufficient insulating capacity to withstand several times the normal operating voltage.

Apart from excessive voltages, the most likely causes of breakdown are foreign bodies too near the upper part of the terminal, or a reduced oil level at the lower half, since the flash-over distance on this lower part of the terminal is generally not designed for air insulation. In apparatus having several leads, when these are insufficiently insulated, there may be

breakdowns between one lead and another. If the leads are placed loose in a tube bushing, the trouble may be due to the insulation being chafed through on the edges of the tube.

It is almost always necessary to replace defective bushings by new ones. Many defects can be prevented by careful mounting, during which the bushings are not subjected to hard knocks or placed in close proximity to the blow lamp used for

FIG. 125. CONDENSER TERMINAL, SHOWING EXPLOSIVE EFFECT OF A PUNCTURE

soldering. In the case of oil-filled bushings, the oil level should be checked from time to time. In most types of bushings, particularly for high voltages, glass expansion chambers or glass gauges facilitate continual observation. Equipment and framework should be at least as far from the bushings as the flash-over distance for the insulator. The bushing protects itself from breakdowns at very high voltages by reason of its inherent time-lag; and with the short duration of the surge voltage, since this rises appreciably higher than the flash-over voltage, flash-over occurs before an actual puncture.

CHAPTER XXI

TROUBLES IN INDIVIDUAL PARTS OF THE MAGNETIC SYSTEM

1. Active Iron. The typical iron trouble in transformers is the building up of eddy current paths in the iron core around parts carrying magnetic flux. If the ratio of the induced voltage to the resistance of the eddy current path reaches a sufficiently high value, the actual eddy current may cause heating at certain places, even to the extent of melting the iron. Upon this, the resistance at the place concerned generally increases, the production of heat is less, and the trouble gradually ceases. On the other hand, the eddy current may start the damaging process elsewhere and even become greater, not necessarily anywhere near the previous place. The very marked heating of the damaged places causes charring of the adjacent insulation material and probably the formation of further local eddy current circuits. It can be seen that this type of iron trouble may spread to an incredible extent (Fig. 126).

Experience has shown that such a process may continue for a long time, the short circuit "burning itself out" many times. Sometimes holes as large as a hand can be found in a faulty iron core. Some of the iron lost from these places may have run out from the iron core, and the rest filled the interstices between the insulation. Drops of melted iron may be found at the bottom of the tank.

Even if the effect has progressed to a considerable degree although the transformer still remains in service, the only external sign of the trouble may be increased humming. If, on the other hand, a Buchholz relay is fitted, the defect will be apparent at an early stage due to the emission of gas. If the damage has progressed until the trouble is at a critical stage, exceptional heating of the oil or even the appearance of smoke is probable. The differential and excess-current relays will operate when a really extensive short circuit has developed in the iron.

After the transformer has been removed from service, the insulation may be tested between the individual clamping bolts and the laminations, also between the groups of laminations

to obtain some idea as to the state of the iron core The testing should be carried out with a supply voltage of 110 or 200 volts, either with a testing lamp or with an insulation tester. It should be noted, however, that even if one or two short circuits per leg or yoke are detected, it does not neces-

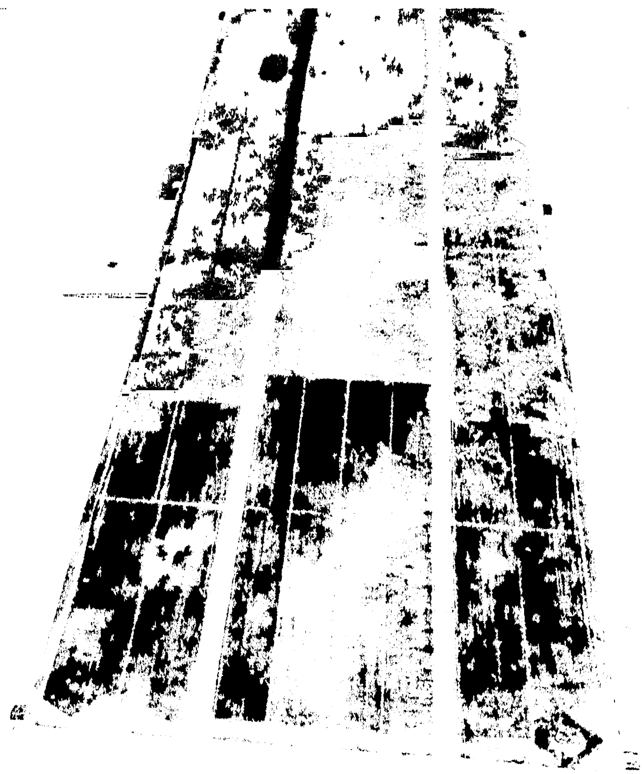


FIG 126 IRON TROUBLE ON A LARGE TRANSFORMER YOKE

sarily follow that the apparatus has serious iron trouble A connection between a clamp bolt and one packet of laminations at a single point is not sufficient to establish a short-circuit path A clamp bolt must be in contact with at least two packets of laminations and at two separate places before a complete short circuit occurs Trouble in the iron can only be diagnosed with certainty when either holes in the iron or drops of melted iron are found.

Iron troubles generally only arise in large transformers, with a core diameter of 12 in. or over. With smaller iron cores, the voltages in the eddy current path are hardly sufficient to overcome the insulation resistances which exist even with bad constructions or deteriorated insulation. Iron trouble is actually very rare in spite of the continual increase in the size of transformers.

The cause of this trouble is in almost all cases insufficient cooling of particular parts of the iron core The cooling may have been deficient from the beginning due to faulty design, or it may have been reduced by deterioration of the oil in oil-immersed transformers, or by accumulation of dust in air-cooled transformers. Excessive local heating may char the insulating material and so allow current paths through it. A less frequent cause of breakdowns of the insulation in the iron core is damp which has been present in the core from the beginning due to insufficient drying. Any damp which has accumulated in the oil during operation will have damaged the winding insulation before it affects the core. Bolts which have not been locked, and which have become loose either in transport or due to natural frequency vibrations during operation, may be responsible for loose laminations and the cutting through of the bolt insulation. When there are badly fitting adjoining surfaces between the yoke and the legs, the insulation between laminations adjacent to this joint may be damaged. It must be admitted, however, that transformers constructed with the experience available to-day very rarely exhibit these faults, except in cases where there is excessive and continued over-voltage of the supply and consequently normal magnetic saturation is exceeded. Large portions of the magnetic flux then seek a way through the clamp bolts and cause eddy currents in the solid metal of these, sometimes burning the bolt insulation. The damage caused by iron trouble can be cured in its initial stages by renewing the insulation of the bolts and grinding with an emery wheel the burnt places in the iron on the surface of the core. Slight short circuits between laminations can often be burnt out with a small auxiliary transformer giving about 2–3 volts and 100–200 amperes. When the trouble is extensive the iron core should be sent back to the manufacturer and the plates, bolts and insulation replaced.

Iron trouble is unlikely if the core is divided into suitable sections; the insulation is then usually sufficient when the

manufacture is carried out carefully in clean conditions, as will be the case in any good modern factory.

"Humming" of transformers arises from the periodical alternations of the magnetic forces between individual parts of the iron core. Every transformer hums when it is on supply but the degree of humming varies very much. It naturally increases in proportion to the size of the transformer, and is affected to a marked degree by the resonance conditions of the tank, plain tanks not being in this respect as good as ribbed ones. In most cases the unpleasantness of humming is more affected by the acoustic properties of the room in which the transformer is installed than by any other factor.

Transformers with interleaved yokes and legs are generally less given to humming than those with butt joints. If, however, the latter have good joints between opposed surfaces and there is sufficient pressure, the humming is not likely to reach a troublesome degree. When the noise is excessive the transformer should be withdrawn from service and tested with a 5 thousandths of an inch feeler, the pressure between the jointed surfaces being increased if necessary to give a proper fit.

It happens sometimes after the transformer is put into service, particularly in the case of high voltages, that, in addition to the normal humming, a sharp crackling sound can be detected. There are always parts of the iron core which cannot be properly earthed, and these receive from the inner winding a capacitance charging current which passes over the point of weakest insulation in the form of sparks to earth—for example on a pressboard insertion between the yoke and the clamp plate. This causes the noise described, but the energy of the sparks is so small that they do not generally cause any damage. The insulation may, in course of time, become slightly charred locally, and this provides sufficient earthing so that the noise ceases. If, however, this does not happen a connection should be fixed for earthing purposes.

2. Supports. By supports are to be understood the end plates of the iron core, the winding supporting frames and brackets, the winding clamp rings with the screws and tension bolts, the yoke clamp plates, and yoke clamp bolts. All these parts have primarily to be suitable for their mechanical purpose of carrying the forces due to pressure or support. They must also withstand the greatest short-circuit forces which may arise,

or the transformer may break down on the occurrence of any appreciable supply short circuit. Transformer construction has now progressed sufficiently for the forces likely to occur to be calculated, and the supports can be suitably dimensioned. Mechanical trouble in iron supporting parts is very rare in modern transformers. It should be mentioned that, for large outputs, circular, concentrically arranged windings are practically universal to-day, since with these the forces due to the main current are exerted on the winding copper. In the case of sectionalized or sandwich windings, the forces due to the main current operate axially and must be taken up through the supports, and particular care is necessary in dimensioning the latter for outputs above 3 000 kVA.

When supporting parts give rise to defects, it must be determined whether the trouble is of electrical or mechanical origin. The winding clamp rings as well as the yoke clamp plates are usually separated from the yokes by insulation distance pieces or pieces of pressboard. Between yoke clamp plates and yoke are generally inserted insulated dowel pins. When there is extensive deterioration of the insulation, or if it is bridged over by foreign bodies, there may be a short-circuited path linking parts of the yoke flux. In addition, the transformer may have winding clamp rings only slotted at one place and equipped with insulated connection screws. In this case the separating insulation needs only to be bridged over at one place for a short-circuit path to be formed round one leg. Trouble then develops in the same way as described in the previous paragraph on iron trouble.

Short-circuited paths may possibly be caused by the cutting through of the insulation as a result of movement due to transport over a considerable distance. When the active part is not sufficiently securely fixed in the tank, it may vibrate with the jolting of railway wagons, ships, or lorries, and in time extensive damage may be caused to the insulation. The damaged part may pass unnoticed at first, and will only break down due to foreign bodies or dirt as a result of careless treatment of the transformer. These defects will generally be noticed so early that they can be cured by replacing the defective insulation.

Parts of the supporting gear may become statically charged even causing sparks, and to prevent such undesirable sparking, the parts affected should be earthed. For large transformers

it is desirable to carry out the earthing through resistances. These ensure that should a fault to earth arise, no dangerous earth currents can flow through the earth connection. For conducting away static charges, the thinnest resistance wire is usually sufficient.

CHAPTER XXII

TROUBLES IN THE COOLING SYSTEM

1. Oil Tanks. The oil tank may fail in operation, to a greater or less degree in both of its functions, that is, as a container and as a conductor of heat. As a container, it has not only to enclose, but also to prevent access of moisture or dirt to the oil, and in this connection the change in oil volume with temperature must be taken into account.

The worst fault is when there is a sudden leakage while the transformer is in service. If the loss of oil is not noticed before the winding has become exposed due to the drop in oil level, a winding defect will most likely ensue and the protective gear of the transformer will trip out. If this takes place rapidly, it reduces the danger of the oil being ignited. These leaks, however, do not often occur in service. The usual cause is a breakdown to earth of the winding, or an earth between the oil tank and a lead. Badly welded joints are also a possible cause of trouble. Transformer tanks are to-day almost exclusively welded, due to the progress made in welded work. It may occasionally happen that the mechanical effect of transporting the transformer causes a welded seam to be no longer oil-tight.

Often defects of this kind can be cured by caulking, in the case of boiler plate tanks. If the trouble is confined to one place, a small area of metal should be hammered in the sound material immediately in its neighbourhood, and the leak closed as a result of the spreading sideways of the metal. Caulking of cracks can be done in the same way with a chisel. In other cases, tin soldering may be found effective, after which the surface of the iron should be smoothed out with a file. Open fissures should be welded together. In urgent cases, to prevent much loss of oil, oil-immersed transformers may be electrically welded. With autogenous welding, the transformer tank must always be emptied.

Dripping oil drain cocks can be cured by tightening up or by fitting a blank plate. Something of this kind is to be recommended on every oil drain. Oil drain screws can usually be relied on to remain tight, and rarely become loosened in transport.

The cover of the transformer tank, in the case of those transformers having an oil expansion chamber, must be bolted tightly to the case. A suitable packing medium is cork linoleum. If necessary, the tightness should be improved by tightening down bolts. When putting on new material of this kind, it should be vaselined so that when the transformer has to be opened at any later date, it will not be stuck too firmly to the surfaces of the joint. In the case of outdoor transformers, it is unlikely that the lid will be penetrated by damp, but there is the possibility that the cement between flanges and porcelains may be a poor, non-watertight, material and disintegrate, allowing water to get into the transformer. If a good cement is used, this will not happen. Cemented places are less resistant to oil (see Chapter XXXIX, para. 3), and on that account there is very often a special packing washer between the flange and the porcelain.

Damp may be carried into the oil in badly constructed transformers due to the "breathing." In transformers without expansion chambers, for installation indoors, and also for use in the open air, there must be a sufficient circulation of air so that no water condenses under the lid. In the first case, a gap should be left open all round between the lid and the lip of the tank. In the second case at least two openings at different heights are necessary so that as a result of the heating up of the air, it is maintained in continuous circulation. For further security, a heat insulating layer is often introduced under the lid. The breathing openings should not only be protected against ingress of rain water but also against dust. To achieve this, the air on its way to the inlet opening should pass through several baffles. In the case of outdoor transformers with oil expansion chambers, air drawn in as the oil level sinks is taken through a drier, in which the air is sucked over a hygroscopic substance such as calcium chloride. This substance should be renewed from time to time, probably at intervals of between two to six months according to the humidity of the air concerned, so that no water is condensed in the oil expansion chamber.

The heat dissipating characteristics of the tank can be spoilt by the formation of sludge in the oil (see Chapter XXXIX, para. 5). Stray losses may also arise in the tank itself, since if the wave shape of the voltage or current curve is very distorted, due to causes external to the transformer, leakage fields will form in the tank metal. These result in eddy

current losses. That part of the tank extending above the level of the windings is particularly liable to this trouble. Such additional heating can often be located merely by feeling with the hand along the tank. Naturally, the normal decrease in temperature from the upper to the lower parts should be kept in mind when doing this.

Transformers with current loadings of from 600 to 1 000 amperes at 50 cycles are often subject to heating by eddy currents arising when the lid forms a closed iron path around the individual conductors. If the lid is slotted between the terminals corresponding to each circuit, this defect can be avoided. The slots should be covered with conducting material such as copper, brass, or bronze which, however, must not be magnetic. The actual cause of the eddy currents is the strong magnetic field around conductors, and this can be very simply prevented by a break in the iron path of a few millimetres.

The oil tank should always be earthed, so that it does not become charged under the influence of the windings and thereby endanger persons coming into contact with it.

2. Oil Coolers. Oil-immersed transformers with air cooling have to be equipped with auxiliary cooling devices when the surface area of the oil tank does not provide sufficient cooling. These cooling devices are either built directly on to the oil tank as radiators, or made up into a battery and mounted independently. In the latter case, there is generally forced oil circulation by means of a pump. Similar cooling devices are used in conjunction with fans for forced ventilation. Such coolers which have welded in tubes or a corrugated cover may leak due to mechanical damage. The comments made in the previous paragraph in regard to oil tanks which have become leaky apply also in this case. It may be necessary to tighten the fixing bolts on the flanges to compress the packing layer more tightly. If oil sludge forms, the cooling effect can be seriously interfered with as in the case of oil tanks, since the oil circulation is restricted. If, however, there is merely a slight accumulation of sludge, it is sufficient to swill the radiators with benzole to remove it. With the types of oil used to-day, these measures may not be successful, and in these cases a thorough washing out with hot oil will clean the radiators. (See Chapter XXXIX, para. 5.)

If the radiator of a transformer is vibrating in service, this is likely to be because the fixing bolts have become loose due

to the shrinkage of the packing material. Resonance vibrations caused in this way can be cured by tightening the bolts, which should afterwards be locked. If tightening on the flanges is not effective, the radiators should be made rigid by welding stiffening strips of sheet iron on opposite sides.

Transformers with internal cooling by water tubes may have water in the oil as a result of leaky cooling tubes, since the water inside the cooling tubes is at a higher pressure than the oil outside the tubes. In the case of external water cooling where the oil is kept in circulation by pumps, it can be so arranged that the oil in the cooler is at a greater pressure than the cooling water. The water in this case should be allowed free egress from the cooler, and the control valve should be fixed on the inlet side. If there is any leakage, the only consequence will be the leakage of oil into the water.

The cooling tubes, according to when they were installed and the individual manufacturer, may be made of iron, tinplate, copper, brass or bronze alloys. The behaviour of these materials as regards corrosion, and the formation of scale in the container, are described in Chapter XXXVII, paras. 5 and 6. It is important that the tube system be subjected, before being installed, to a pressure of several atmospheres, so that any leaky places can be detected and repaired. The flange connections should be packed with cardboard treated with linseed oil. Quite a good design of cooler has vertical water tubes which open at the bottom into a water chamber into which the impurities of the cooling water can fall. This water chamber can be removed easily and cleaned. If two coolers are used on a transformer, the cleaning can be carried out without any interruption of the working. If the cooling water is very dirty a filtering device is necessary, and with the standards prevailing to-day it is possible to build coolers which will withstand the service conditions almost indefinitely.

CHAPTER XXIII

TROUBLES IN CHOKE COILS

1. Iron-cored Choke Coils. Almost the same defects may occur in choke coils with iron cores as those described for the different parts of transformers, and, in addition, some due to the so-called *air gap*. In order that current and voltage of the choke coils shall be proportional as far as possible up to the highest loading, the greatest part of the ampere-turns must be taken up by the air gap, while only a small remainder is absorbed on the iron path. It is well known that the magnetic field tends to spread at the air gap as in Fig. 127, in an endeavour to reduce the saturation and find a smaller reluctance. The spreading of the air gap flux may even extend in amongst the neighbouring windings. The flux spread is more extensive the greater are the ampere-turns on an air gap, and the greater the distance between the iron core and the winding. If these ratios are very bad, the flux proceeding at right angles to the layers of laminations from the iron core crosses so markedly through the outermost sheets that excessive heating is produced by the eddy currents. This may cause the insulation on the laminations to be burnt, and the same symptoms are exhibited as in the case of iron trouble in a transformer. In addition, the end plates and clamp bolts near the air gaps may be overheated by eddy currents, and cause damage to the insulation and oil. If the winding itself is made from wide copper straps, these are subject in the same way to additional losses.

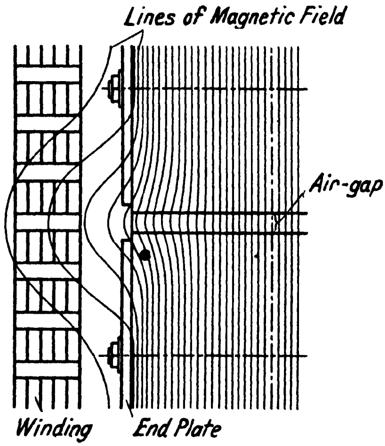


FIG. 127. SPREADING OF THE MAGNETIC FIELD AT THE AIR-GAP OF A CHOKE COIL

Since the cause of this trouble, as already mentioned, arises from too much variation in the distribution and concentration

of the induction and absorption of the ampere turns, a cure can only be effected by a complete reconstruction improving these conditions. The air gaps should be subdivided, that is, instead of several large gaps, a number of smaller ones should be provided. Unsymmetrically tapped windings should in some circumstances be so altered that, by changing the tapping, no flux displacements occur in the manner indicated above. This is achieved when the tapped winding parts are distributed over the whole core length, or are inserted or arranged concentrically in the remaining winding.

2. Air-cored Choke Coils. For limiting the short-circuit currents in switchgear, air-cored choke coils are used. At peak currents these exhibit a constant reactance, since no saturation phenomena can occur. In plants with large outputs these coils are subject to severe demands when a short circuit occurs, not only electrically but mechanically and thermally.

They are subject to heavy electrical stress since, at the beginning of short circuit, there may be on the coil excess voltages of short duration which may be twice as high as the full working voltage.

Mechanically they must withstand the forces arising from the high initial short-circuit current, the peak value of which may be equal to $2\frac{1}{2}$ times the steady short-circuit current.

From the heating point of view, severe loading may arise, since the coils may be on overload and in addition, on account of the time-constant of the windings, suffer a rapid increase in temperature when the short circuit develops.

In all these characteristics, the reactors must have the same margins of safety as the machines and transformers.

As a result of unfortunate experiences when current limiting choke coils were first made, these are now required to be constructed only from non-inflammable materials, so that even with a failure a fire is avoided. The windings and coils are spaced with concrete, asbestos cement, or porcelain materials. For high voltages over about 15 kV., in most cases simple space insulation by air is no longer sufficient, and the conductors must be wrapped round with mica or asbestos, or both.

With insufficiently insulated coils, particularly those with bare conductors, if damp or dust is present there is every likelihood that on the occurrence of high peak voltages a short circuit will arise, also a flash-over between the turns of the coils or windings. The winding short-circuited then forms a

short-circuited loop in which the transformer effect of the remaining windings produces a very high current. This generally leads to serious damage of the short-circuited part of the winding. Choke coils with concrete or asbestos cement insulation should be given a thick coating of varnish as a protection against damp and dust. At higher voltages the best protection is to employ thoroughly impregnated insulation as used in motors and generators.

On stranded conductors, due to the current displacement with very large current peaks, considerable voltage differences may arise between adjacent wires on the surface of the conductor. In this case, burning of the copper wires may occur even though the outer insulation is good.

Due to vibration, insufficiently clamped coils may become loose and the whole winding collapse.

In some conditions, any subsequent short-circuit peak may cause the adjacent turns to touch one another, and the mechanical construction should be such that the winding can be easily pressed back into place. After this, incidentally, nuts should be locked. In a good construction, the number of spacing pieces is so great that the conductors are only unsupported for short distances.

In spite of the use of non-inflammable insulating materials, the loading as regards heat is ultimately limited due to the fact that copper softens at high temperatures. The permissible copper temperature of 250° C. specified in the U.S.A. Standards may be taken as the maximum.

Joints soldered with soft solder are a source of danger to the coil, since if they are heated unduly the solder may easily melt and flow on to the insulation; also an open circuit will probably develop. Connections should therefore be silver soldered or welded.

The three coils of a three-phase group are often mounted one under the other for reasons of space. In this case, it is expedient to provide a good support against the walls and cover. Also choke coils fixed adjacent to one another should be supported on opposite sides, since with polyphase short circuits, mutual forces occur between the coils. It should be further noted that iron objects near the choke coils are not only heated by eddy currents, but can even be drawn towards the coils by short circuits. No iron tools or other apparatus should be in the vicinity of the coils, which are best contained

in closed cells. If the cell walls are near the coils, no iron must be contained in them nor in the doors. Cases have been known where iron cell doors have been torn from their hinges and drawn against the reactors.

The reactance of current-limiting choke coils should as a rule be designed to absorb not less than 5 per cent of the normal voltage of the supply with normal current flowing, since otherwise the ratio of the short-circuit current to the normal current is too large. If only a smaller value of reactance is practicable from the point of view of maintaining the voltage in normal operation, a choke coil with a suitably higher rated current strength must be chosen such that at this rated current strength there is 5 per cent reactance voltage. The voltage drop is then with the smaller operating current proportionately smaller.

The methods of construction of choke coils are at present in a state of development. It is a matter of opinion whether, at least for higher voltages, it would not be better to drop the demand for non-inflammability, and substitute for it a design having more regard for heating and better insulation of the conductors with paper and cotton covering, also perhaps even to introduce oil insulation.

CHAPTER XXIV

INDUCTION REGULATORS

THE air-cooled induction regulator is similar in its construction to the asynchronous machine. On this account one section of the troubles of asynchronous machines may also be applied to induction regulators. This group comprises breakdowns to earth, short circuits between turns, distortion of the coil ends, and excessive eddy current losses in the windings and constructional parts, as mentioned in Part 1. The parallel operation of induction regulators requires phase control, in order to avoid circulating currents when paralleling and adjusting for the voltage.

Iron troubles are hardly ever met with in induction regulators. On the other hand, marked humming may occur, caused by vibrations of the rotor if the shaft has too much play in the bearings. Induction regulators are sensitive in this respect, and in bad cases it may be necessary to renew the bearing bushes. If the trouble is not so serious, it may be sufficient to place steel strips under one side of the bearing shells somewhat out of the plane of rotation, so that the bearings are slightly canted. Further reduction of the noise may be effected by erecting the machine on a soundproof foundation.

Failures of the moving parts depend greatly on the construction and design. In many cases, dirt is the prime cause.

Oil-cooled induction regulators have an additional possible source of trouble in their tanks. The nature of these troubles and of those for the oil are exactly the same as in the case of ordinary oil-immersed transformers.

The switchgear associated with induction regulators is discussed in Chapter XXXIII, para. 7 (*b*).

PART III

AUXILIARY APPARATUS

CHAPTER XXV

GENERAL TROUBLES IN INDIVIDUAL PIECES OF APPARATUS

1. Excessive Heating of Magnet Coils. The results of excessive heating of electrical conductors are the same in apparatus as in machines and transformers. The only difference is that continuous mechanical stresses, due to the rotation, which occur in machines, and which aggravate the effects of overheating, generally do not arise in switch and control gear.

Excessive heating in apparatus occurs generally on magnet coils and contacts. In the case of magnet coils it is important for the operator to have some definite data for the permissible loading in order to guard against serious mistakes when renewing such coils. The knowledge of a safe loading figure is particularly necessary in avoiding mistakes when using alternating and direct current coils.

In the case of direct current coils a knowledge of the ohmic resistance alone is sufficient to determine its operating current at rated voltage, and therefore its power requirement. On the other hand, the current of an alternating current coil is generally fixed by the reactance, which usually exceeds very considerably the ohmic resistance. Generally also this reactance, as well as the iron losses in the magnetic circuit of alternating current coils, will not be known, so that neither current nor power required can be calculated. With a knowledge of the ohmic resistance, and on finding that the current and loading are much too great when supplied from d.c., one can be certain that the coil concerned is an a.c. coil.

In order that magnet coils for either type of supply should not be excessively overheated, the loss should not amount to more than about 0·4 to 0·65 W. per in.^{2} of their surface.

Overheating on properly designed direct current coils generally only occurs as a result of short circuits or breakdowns

to earth, which in turn are usually due to damp insulation or mechanical damage.

An important cause of dangerous overheating of alternating current coils is the "locking out" of the armature in the open position. The magnet coil in this condition takes a much larger current than with the armature closed, and the coil overheats in a relatively short time. Overheating may also arise as a result of bad design of the iron constructional parts in the magnetic circuit, so that eddy currents can form and the winding receives additional external heating from this source.

Short circuits between turns mainly occur on alternating current coils, since here the voltage between turns is greater than on direct current coils. The former are also more liable to vibration since the iron core, particularly at low frequencies, is very liable to vibrate.

2. Overheating of Contacts. The heating of a contact is influenced by the magnitude of the current loading, the contact pressure, the surface area, and its cooling properties.

Excessive heating of contacts usually starts in the first place when, on exceeding a certain temperature, the contacts become oxidized. The contact resistance is thus raised, ultimately the contacts become red hot, and finally are welded together, just as in the case of resistance welding used in workshops. The cause of this process is unusually high local contact heating and also, according to the heat-conducting capacity of the surroundings, considerable temperature increases of other nearby parts. The final result is probable damage to any adjacent insulating material.

It is first necessary to determine if the contact has sufficient margin of safety against overheating. The dimensioning of the surface was originally done by the maker so that it may be assumed that it was correct, and also that the apparatus when new was properly designed for the totally-enclosed or open construction, as the case may be. The permissible temperature rise above the maximum ambient temperature of 35° C. may be stated as about 35° C. for a contact. If a higher temperature is detected, the construction and loading of the apparatus should be checked to determine if they are as specified. The loading should equal the rated current and the ambient temperature should be observed. If this amounts to 40° C. or 50° C., for example, a contact temperature rise of 40° C.

or 50° C. may be dangerous to the contact, since its total temperature may then reach 80° C. or 100° C. and oxidation occur.

It may be difficult for the maintenance man to decide whether a contact pressure is correct. The value of this may have altered since the delivery of the apparatus and it may be impossible to judge the correct contact pressure for a certain current strength or to gauge it by the hand. The knowledge of a few numerical values is, therefore, useful even if these are only approximately applicable. The normal contact pressures on main current contacts may be taken as—

For brush contacts in air and in oil about 0·9 oz. per A.

For solid contacts up to about 300 amperes about 0·9 oz. per A.

For solid contacts with higher current strengths an appreciably higher pressure is generally necessary on account of other factors, such as sparking on switching in.

Independently of the type of heat-conducting surface of contacts, a certain minimum pressure must be maintained, since the heating occurring on contacts is principally determined by the pressure. This is particularly a matter of importance in the case of solid and roller type contacts. For contacts with very small currents, for example, auxiliary contacts, the values given above are obviously not applicable. Under these conditions a pressure of 5·0 7·0 oz. should be maintained. Auxiliary contacts of precious metals should have a contact pressure of at least 1·75 oz.

A further cause of contact overheating may be the condition of the contacts. Contacts with inefficient extinguishing of the arc may become pitted or oxidized; an almost non-conducting layer forms on the contact surfaces, and ultimately they may become welded together as a result of this. Pitting may also occur from using certain greases on the contacts which are liable to cause oxidation. These are mentioned in Chapter XXXVIII, para. 2. It should be kept in mind that it is better to use practically no grease than to apply too much or an inferior grade.

A further cause of the formation of oxide is the tinning of the contact surfaces. When an arc forms, tin oxide is deposited which is a very poor conductor and causes heating of the contacts. Tinning of contact surfaces should therefore be avoided.

In the case of oil-immersed copper contacts it is often noticed that their temperature shows a continuous steady increase so that eventually, for example, with oil-immersed switchgear, too high a temperature of the switch tank is reached. The cause of this phenomenon is a layer of practically non-conducting material on the contact surfaces, caused by oxidation and the formation of copper salts. A chemical analysis of the oil of such switches generally shows an increased acid content and considerable sludge formation. Since the oxidation first arises above a certain temperature, this trouble develops particularly when the oil is continuously heated due to external causes—for example, in starters. Where therefore there is a comparatively high average oil temperature, contacts should not be loaded to normal values, but the loading should be suitably reduced. The dangers of excessive oxidation can be very effectively minimized by avoiding leaving a live contact uninterruptedly switched in for several months. It is good practice to switch out contacts every now and then and thus to break up the oxidized layers.

A test which gives reliable information as to the state of contacts is the measurement of the voltage drop with direct current across the contact places, not only at the manufacturer's works before the apparatus is put into operation, but also after a certain period in service. This method is, however, seldom practicable in service since it requires for successful results direct currents of several hundred amperes. Where possible, however, it enables those places in the circuit which are the cause of the overheating to be determined. This test has the advantage that it gives an accurate indication of changes that take place in the apparatus, as compared with its original state.

3. Excessive Contact Wear. All contacts on control apparatus such as controllers, starters, relays and such gear, which are principally used for making and breaking a current-carrying circuit, are subject to burning. When opening a circuit, energy is released between the separated contacts which is expended in heat, and causes heating of the air and of the places on both contacts where the arc arises. At these places a certain amount of the contact material is heated to melting point and partially vaporized. The arc, particularly with direct current switches, is blown out to a considerable length by the magnetic blow-out field arranged at right angles to the

direction of the arc. This arc extinguishes itself almost instantaneously, since the voltage required to maintain it is more than the working voltage. The wear and tear on the contact is dependent on the current and voltage, on the frequency of the switching, and on the quality and hardness of the contact material.

The loss of material due to burning is very different for alternating and direct current, and is not directly proportional to the load which is switched out, but usually dependent to a much greater extent on the current. The wear and tear on the contact under similar conditions varies, and even with an equal number of switchings, according to whether these take place at longer or shorter intervals of time. It is obvious that with very short time intervals between switchings, the contact has no time to cool off between two successive operations and therefore becomes hotter.

The contact material is the most important factor in connection with loss by burning, since the melting point varies with the material. Even in the same material the loss also varies with hardness, and it has been shown that this loss decreases very rapidly for degrees of hardness between 30° and 90° Brinell hardness, but above this less so. The hardening of contact materials above this limit is usually of little value.

Very little loss occurs on contacts of precious metal, particularly silver, when in the hard pure metallic state. Silver contacts have the great advantage that the silver oxide produced by the arc is an electrical conductor.

It is surprising to find that the pitting normally occurring on contacts, as discussed in para. 2 of this chapter, as a rule forms much more readily on switches for low currents than on heavy current switches. From tests it is evident that this peculiarity is due to the fact that on switching out heavy currents the pitting of the contact surface is much more coarse grained than when dealing with smaller currents. This coarse grained contact surface is more readily crushed by the impact on switching in than the fine grained surface. The same effect is obtained in another way with roller contacts, as the contact surfaces at each switching operation are rubbed against one another. In this case, however, under otherwise equal conditions the loss of material is much greater than with solid contacts.

In particularly bad cases, as much as 100 volts may be

necessary to break through the oxide layer on contacts. This condition of contacts in an excitation circuit may have very unfortunate results. Contacts in which the resistance must be maintained permanently at a minimum—for example, with braking current circuits for traction purposes—must be so constructed that oxide formation never occurs under any circumstances.

In direct current switches the loss of contact material is largely dependent on the nature of the switching out. Usually the more quickly the arc is driven away from the place where it starts, the smaller is the loss. This is easily understandable, since the longer the arc is maintained at the same place, the more contact material is melted and vaporized at these points. If, on the other hand, the arc alters its position rapidly, as in the case of switches with magnetic blow-outs, and arc horns, only the parts of the contacts other than the actual contact surfaces are heated to melting point. By arranging arcing horns on the contacts it is frequently possible to lessen very considerably the loss on the actual contacts.

In air-break alternating current switches, the switching conditions are quite different. The arc generally extinguishes itself at the point when the current reaches zero. On this account, only one, or a few, half waves occur, and the electrical energy is appreciably smaller, at least with non-inductive circuits. For this reason no special improvement in extinguishing is obtained by blow-outs. Nevertheless with alternating current above a certain value, use is made of magnetic blow-outs to prevent the arc reforming after extinguishing at the zero point, due to the voltage rising again at a particular opening of the contacts. Only with low voltages, below 150 volts, is it usual to dispense entirely with blow-outs, or some other expedient for extinguishing the arc. In the case of a.c. oil-immersed switches, the contact loss by burning, other conditions being equal, is much greater than on air-break switches with arc blow-outs.

Direct current oil switches should as far as possible be avoided for use for breaking circuits on load. The energy of switching is in this case much greater than in a.c. switches, and the arc causes such a marked carbonization of the resinous constituents of the oil that after only a few switchings the latter becomes opaque and the contacts very dirty. The chemical process is described in Chapter XXXIX, para. 5.

The oil has to be examined frequently and if necessary filtered. In addition, the switch frequently has to be cleaned along its sliding surfaces on account of the heavy deposition of carbon.

With air-break switches, in addition to burning of the contacts there is burning of the arcing chamber, its extent depending on the inflammability of the materials and the

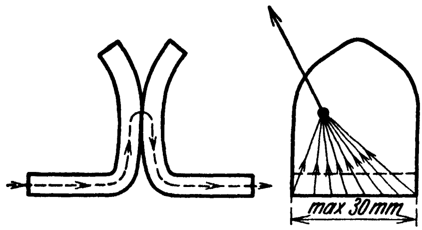


FIG. 128A. TYPICAL CONTACT SHAPE
Excessive width allows strong sideways forces on the arc.

efficiency of the switching out. If the arc is blown out perfectly straight, its path cuts the arc chamber at a tangent and has very little effect on it. If, on the other hand, the arc is blown on to the arc chamber walls, these are soon burnt through. This generally happens with unsuitably shaped contacts, but can be avoided by shaping the contacts as shown in Figs. 128A, 128B, and 129. For each contact there is a "critical breadth"

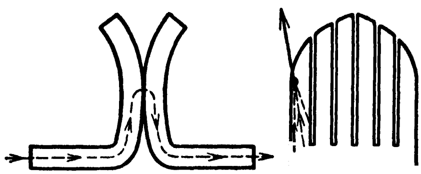


FIG. 128B. CONTACT DIVIDED BY SLITTING TO REDUCE THE SIDEWAYS COMPONENTS

below which the arc, even though it strikes on the outermost edge of the contact, is yet always led in the proper path parallel with the arc chamber. If, however, the contact breadth is too great—that is, more than about 1·2 in.—the sideways current component (Fig. 128A) and its particular magnetic field in the contacts and in the arc are too great. The arc then strikes into the arc chamber and remains in this position, in which it causes damage to the contacts and to the arc chamber.

The loss by burning of the contacts and the arc chamber can be reduced by slotting the contacts as in Fig. 128B, which reduces appreciably the sideways component of the current. The slots must, however, have a certain minimum width, since, otherwise on switching operations they will become welded together.

The proper shape for a butt contact is shown in Fig. 129. The building up of a strong sideways component is prevented by chamfering the corners. The current path is here used for maintaining the external blow-out field.

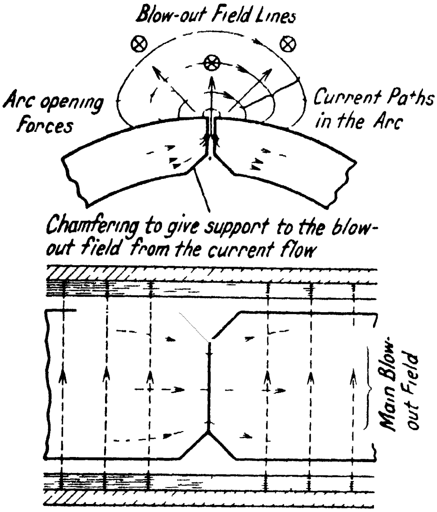


Fig. 129. Suitable Shape for a Butt Contact

When switching is associated with re-ignition, there may be also greatly increased loss of material from the arc chamber. Fig 130 makes clear the process when switching a large current with ordinary contacts. As long as the places where the arc strikes on the inner sides of the contact horns move upwards, their distance increases continually. After passing over the tips of the horns the arc, however, may travel farther on down the backs of the horns, which brings the striking places nearer together again so that the strip of air already ionized will continue to have an arc across it which will probably burn sideways into the arc chamber. Arcing horns are also an effective protection against this. Their action can be seen by comparing Fig. 131 (*a*) and (*b*). Both contact shapes were subjected to the same breaking kVA. with the same speed of break. The increased burning

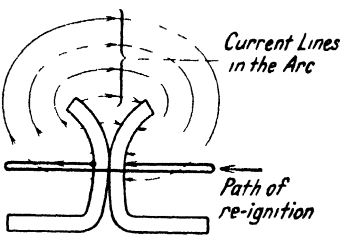


Fig. 130. Re-ignition of Arc on Contacts without Arcing Horns

of the arc chamber, indicated by the complete burning through of the arc shield in the case of the contact without horns, can be seen at a glance and can only be explained by the re-ignition of the arc.

Burnt places noticed on butt, roller, or other oil-immersed contacts are often quite unnecessarily a source of worry to the maintenance staff. These contacts, even butt contacts, which in their new condition made contact over a surface, may

(a) (b)

FIG. 131 BURNING OF ARCING SHIELDS BY THE ARC WITH VARIOUS CONTACT SHAPES

(a) Contact without arcing horns Arc shield burnt through
(b) Contact with arcing horns Arc shield very little damaged

later make contact at one point only. The loss by burning, therefore, does not make the contact pressure any less than might have been expected in any case. Only the loss of material which occurs finally sets a limit to the burning, and settles when contacts must be replaced

4. Insufficient Insulation. Apparatus operating in air sometimes exhibits insulation faults in the form of creepage tracks. Breakdowns through the insulation are, on the other hand, much rarer. Obviously, the flash-over voltage is fixed by the condition, and, to a lesser degree, by the length of the creepage surface It is therefore necessary to protect the surfaces of the insulation against the accumulation of dust and

dirt. Air-break and oil-immersed switches inevitably form creepage tracks in time, due to carbon forming on switching, and should therefore be cleaned out at intervals.

Dampness is another cause of many of the troubles arising in electrical apparatus. Apparatus fixed in very damp places should at least have a good flow of air through it. Apparatus used on outdoor plant may be affected by condensation of water, due to air, which, entering through the cable conduit, may condense on dangerous places and thus lead to defects. The tanks of outdoor apparatus should on this account be protected against the ingress of air. The simplest expedient is to pack the conduit at the entrance into the tank as tightly as possible with sand.

Relays and protective devices are often mounted on slate panels. Breakdowns through these panels between parts of the apparatus which are under voltage are the result of bad construction, for example, insufficient insulation of the live parts against the panel, or poor quality slate containing veins of conducting material, but before everything, inadequate treatment of the slate by the maker of the apparatus.

In d.c. apparatus, particularly field coils, the insulation may be damaged by electrolytic action, that is, corrosion. This is most likely with single-pole coils which, when switched out, remain permanently connected with one lead to the positive pole of the supply. This trouble can be avoided by connecting the coil lead under voltage to the negative pole, as shown in Fig. 154 (*a*) and (*b*). When coils cannot be connected in this way immersion in paraffin gives protection against corrosion to some extent. In coils with both leads disconnected, this phenomenon generally does not occur.

The use of unsuitable soldering material, i.e. flux, leads to the formation of verdigris and eventually to damage of the insulation.

The breakdown of oil which develops in the oil itself is described in Chapter XXXIX, para. 5. In the present chapter only those causes of breakdown arising in the associated apparatus are discussed. The maximum stress on the oil in apparatus always occurs when a metallic point comes opposite to a metallic plate under voltage. The voltage drop near the point with this arrangement is several times the average voltage drop reckoned on the distance between point and plate. When the point is opposite a curved spherical shape, the conditions

are appreciably improved. This feature is usually considered by the manufacturer during construction, but the maintenance man should be aware of it, in order to be able to carry out repairs on high voltage apparatus. The rule also applies to all those cases where, instead of oil, there are solid insulating materials such as presspaper, or wood, under voltage in the same way. The danger of a breakdown may even be increased by using insulating material with a layered construction such as wood, if the direction of the layers corresponds with the direction of the voltage drop, and a pointed electrode enters in the same direction into the material, as shown in Fig. 132.

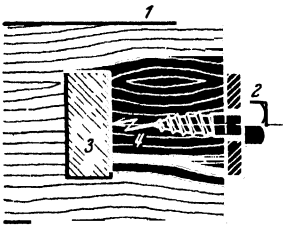


FIG. 132. APPARATUS AFFECTED BY PUNCTURE. TYPICAL LONGITUDINAL STRESSING OF WOOD BETWEEN POINT AND PLATE

(1) Wood cross piece.
(2) Earthed fixing screw.
(3) Live metal part
(4) Position of puncture

Defects are often too readily attributed to breakdowns or flash-overs arising from excess voltages, in cases where the existing insulation distances cannot be punctured by the working voltage alone. There is undoubtedly a tendency to attribute to excessive voltages any phenomena which are not clearly understood, and in many cases excess voltages, the origin of which will not be discussed here, actually are the cause of the trouble. It is frequently, however, advisable to ignore the possibility of excess voltages and first to seek some other explanation. When this is done, badly fitting or loose contact screws on the terminals of oil-immersed switches which may easily cause sparking are frequently detected. Under these conditions, glowing metallic particles may be thrown off and comparatively large air gaps may be flashed over. Finally, a permanent arc to earth or between phases may form. Careful supervision during erection and periodical survey of all possible loose parts of the apparatus usually will result in reduction of the number of supposed "excess voltages." The spanner may often need to be supplemented by a brush, since a dirty condition of the plant, which may be covered with cobwebs, will also cause flash-overs.

An insulation defect is often suspected when a certain amount of crackling noise is apparent externally, but on withdrawing the apparatus from the oil no signs of a defect may be

seen, the oil being in good condition and no foreign matter or creepage tracks visible. This phenomenon may be due to several causes. There may be in the apparatus some device, such as a protective resistance, buffer resistance, heating resistance or the like, intended to be connecting one of the other live parts either to earth or to an external current source, but which is not actually doing so. This device is then electrically at a neutral potential, and according to the capacitance conditions may discharge to earth at a certain voltage so that from outside the apparatus the crackling of charge or discharge sparks can be heard. In many types of switches, the connection with the buffer contact and protective resistances is by sliding contacts which, with heavy switchings, often become coated with carbon so that the contact is ineffective and a defect arises. In these cases, the parts concerned should be tested as regards the good condition of their contacts and connections.

Often in oil-immersed apparatus, constructional parts which normally are electrically at a neutral potential are responsible, and for this reason cause audible discharges. Generally, these parts can be electrically connected either with the remaining live parts or to earth, which puts an end to the trouble. Discharges also occur when apparatus is put under voltage too soon after filling with oil while air pockets still exist in the oil.

Many insulation defects, such as burst porcelain insulators, are caused by internal mechanical stresses arising during either manufacture or erection. During transport, these stresses are probably released and crack the insulators. Bakelized paper insulators may be damaged by atmospheric influences, and varnish coats which are not weatherproof may allow the surface of the insulator to be damaged.

Defects in insulating parts consisting of oil-treated wood generally arise as a result of wrong treatment of the wood, or unsuitable application. Wood treated in this way, when properly manufactured and applied, can be considered a most reliable insulating medium. A conspicuous characteristic indicating the condition of a wood or bakelized paper insulator is the temperature it attains during use. If trouble is suspected, the voltage should be taken off the insulator, which should then be felt with the hand. This method is not suitable for any heating appreciably above the surroundings.

5. Mechanical Faults. Mechanical faults likely to arise may be caused by insufficient lubrication, deposition of carbon,

fatigue effects in apparatus on very heavy duty, or too high a temperature. Other causes may be insufficient resistance against the very varied transient effects, wrongly dimensioned and overstressed springs of all kinds, or mechanical wear in the bearings, pressure places, triggers or other constructional parts. Insufficient lubrication and deposition of soot generally arise in the case of apparatus for use in the open air. Due to marked variations in temperature and atmospheric influences, the chemical permanency of the lubricant may be unsatisfactory. Chapter XXXVIII, para. 2, gives data on the behaviour of certain lubricants in the cold. In outdoor apparatus, particularly isolating switches, the danger of failure of the lubrication is very great, on the one hand because it is only rarely in use and on the other hand because the switch blade itself, or the adjacent parts, remain continuously under voltage and the lubrication on this account cannot be checked. It is therefore particularly to be recommended that in very cold conditions such apparatus should be operated mechanically several times when the opportunity arises. The remarks in Chapter XXV, para. 4, regarding insulating capacity and damp, apply equally to mechanical failures from deposition of soot.

Very often serious failures occur of those mechanical parts which are seldom in use. Accumulations of water on joints and similar places may freeze and jam the apparatus. Provision should therefore be made for the drainage of water from such parts.

The operating mechanisms of oil-immersed switchgear of the open-air type may develop troubles from quite general causes, such as severe frost in winter. The increased viscosity of switch oil at low temperatures may also have a bad effect on switch operation. In plant to withstand very low temperatures, good results are obtained by incorporating heating resistances in the oil tanks. Before the onset of cold spells these should be tested to ensure that they are in an efficient condition.

Troubles with mechanical parts of the apparatus traceable to electrodynamic effects are more minutely described in the sections on those parts they affect. It is generally known that electrodynamic damage is particularly severe in the terminal connections of a.c. generators where it is increased by the very compact arrangement of the conductors. Such troubles often occur also in plant for low voltages, and high short-circuit currents are very liable to occur in these cases. The opposite

is usually the case in high voltage switchgear, and very high current loadings rarely arise. With high working voltages the leads have such large distances between them that electrodynamic effects cannot reach a dangerous degree. With the assistance of the simple formula given below, the maintenance engineer can calculate the effect of a short circuit between parallel conductors and estimate the possible damage.

Two parallel conductors carrying the same current to and from, as in Fig. 133, are exposed to a force calculated from

$$F = 4{\cdot}5 \times 10^{-8} \times I^2 \times (l/a) \text{ lb.}$$

in which

I = current in each conductor in amperes.
l = length of the parallel portion in inches
a = distance between the parallel conductors in inches.

When the direction of current flow is the same in both conductors, the force attracts, when it is different in the two conductors it repels.

Between single-phase conductors, the forces pulsate with the frequency; in three-phase conductors in a stationary condition they are almost balanced and only occur in the case of a short circuit with unsymmetrical current distribution.

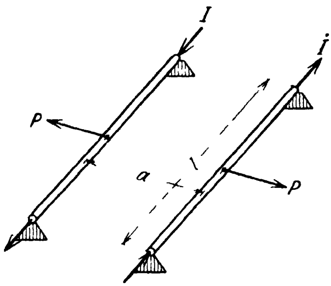


FIG. 133. REPULSION BETWEEN TWO PARALLEL CONDUCTORS CARRYING CURRENT IN OPPOSITE DIRECTIONS BY THE ELECTRODYNAMIC FORCE P

The occurrence of dangerous short-circuit currents is particularly to be expected in low-tension converter apparatus for direct current. Unusually high short-circuit currents occur more particularly in rolling mills in which there are very large d.c. generators generally supplying rolling mill motors. When a short circuit occurs the latter, due to their inertia, all operate as generators and feed into the short circuit. Places likely to be in danger in this way should, therefore, be equipped with very strong supports for the leads.

With displacement of the leads, it is necessary to take care that porcelain supporting insulators are not unduly stressed by the weight of the heavy copper conductors as regards either tension or compression.

CHAPTER XXVI

SWITCHGEAR

WITH direct current, air-break switches are the only ones which can be used in practice, but for alternating current both air-break and oil-immersed switchgear are possible.

1. Air-break Switches. (*a*) BLOW-OUTS. Faulty operation may be traced to the failure of the blow-out when switching out. In such a case the magnetic circuit should be tested with the switch carrying current, to see if it is effectively excited by touching the pole plates with an insulated piece of iron. If the blow-out is correct, a light magnetic pull corresponding to the normal current can be clearly felt. In bad constructions, leads to the blow-out coils or their windings may be partially short-circuited by the arc. When switching out weak currents, appreciably below the rated currents at a high contact voltage, a failure may easily occur if the blow-out is too weak or the distance between the opened contacts too small. If the blow-out field system consists mainly of solid iron or iron with excessive residual magnetism on direct current, the arc may even be forced into the switch. This is particularly likely when, immediately after handling a strong current in one direction, a weak one in the opposite direction has to be interrupted.

When switching in alternating current air break switches, an arc is often observed which is not always due to unsuitable construction of the contacts. The arc occurs, particularly with high voltages, simply as a flash across the decreasing space when the contacts are approaching one another before the final position. This phenomenon can be prevented by raising the speed of switching in, to the maximum possible.

(*b*) ARC LENGTH WITH DIRECT CURRENT. When air is ionized by an arc, its dielectric strength is greatly diminished. If the arrangement of the arcing chamber is not good, breakdowns to earth may arise as a result, or the arc itself may seek a path other than that provided for it. It is obvious also that a short-circuit load to be switched out may exceed the rated capacity of the switch. If the highest load (highest current and voltage) to be switched out by the switch is known,

its arc length on switching out a non-inductive circuit can be approximately determined from the following formula—

$$l = 0 \cdot 12 \times V^{0.7} \times I^{0.36}$$

in which

V = recovery voltage.

I = working current before switching out in amperes.

l = the approximate arc length in inches.

By means of the curves in Fig. 134, it is possible to determine graphically the approximate arc length from the known

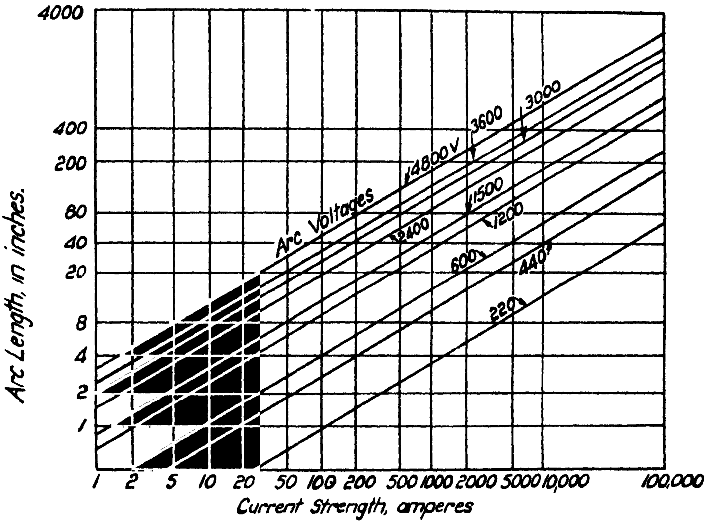


FIG. 134. LENGTH OF THE D.C. ARC RELATIVE TO CURRENT AND VOLTAGE IN A MAGNETIC BLOW-OUT FIELD WITH ABOUT 500 GAUSS INDUCTION, AND A NON-INDUCTIVE CIRCUIT

values V and I. From this arc length it can be seen whether the switch has sufficient space to allow the drawing out of the arc without breakdowns to an adjacent phase, or to earth, occurring. The arc lengths found by means of the above formula can be appreciably shortened by incorporating cooling devices in the arc path. The cooling, however, tends to encourage excessive switching-out voltages and cannot, therefore, be carried out to any great extent.

(c) OVER-VOLTAGES. Highly inductive circuits make switching out appreciably more difficult, since the magnetic fields of

the inductances which have to be destroyed on the interruption of the current cause high over-voltages, which arise on the switch contacts and, in some circumstances, may amount to many times the working voltage. The over-voltage not only increases the switching load, but the work of switching out with an inductive circuit is much greater since the whole of the energy of the magnetic field flows into the arc. Consequently much more gas is developed than when switching out circuits without inductance.

The magnitude of the over-voltage is usually particularly dangerous in inductive auxiliary circuits, such as field coils, where the magnetic circuit has its path solely in the iron and the large number of turns introduces a very large inductance. If such circuits are broken by switches having magnetic blow-outs or by contacts immersed in oil, an excess voltage amounting to several thousand volts may quite possibly arise. This is the cause of many flash-overs in auxiliary circuits, which often appear quite incomprehensible. When blowing of fuses which cannot be explained occurs in d.c. auxiliary circuits, the cause should be sought in this direction.

An effective remedy consists in arranging a non-inductive resistance in parallel with inductive coils through which the released magnetic energy can flow away and be dissipated. The circuit-breaker arc then becomes very small. If possible, this resistance should be made the same size as the ohmic resistance of the circuit to be isolated, because then its effect is greatest as regards the value of the over-voltage. Switches intended for interrupting the field circuits of electrical machines are usually constructed with a discharge resistance. When switching out in this case, the resistance parallel to the coils is first switched in, and then the main circuit broken.

A further protection against over-voltages, principally on auxiliary coils in circuit with relatively light switch contacts, is the parallel connection of condensers, which absorb the released energy and reduce the arc.

2. Oil-immersed Switches. The actual processes during the switching out of an alternating current under oil are of a very complicated nature and they will not be discussed in detail here. The most important from the practical point of view will, however, be explained.

(*a*) Pressure Explosions. The so called "oil piston" theory of switching out is to-day generally confirmed by

switchgear practice. The arc under the oil produces gases by decomposition. These gases compress the oil which can only expand upwards, so that an ascending oil piston forms If this reaches the switch cover, and more gas is developed during the time the arc continues to burn. excessive pressure occurs inside the switch. The pressure arising from this process may exceed the pressure capacity of the swit h, when an explosion

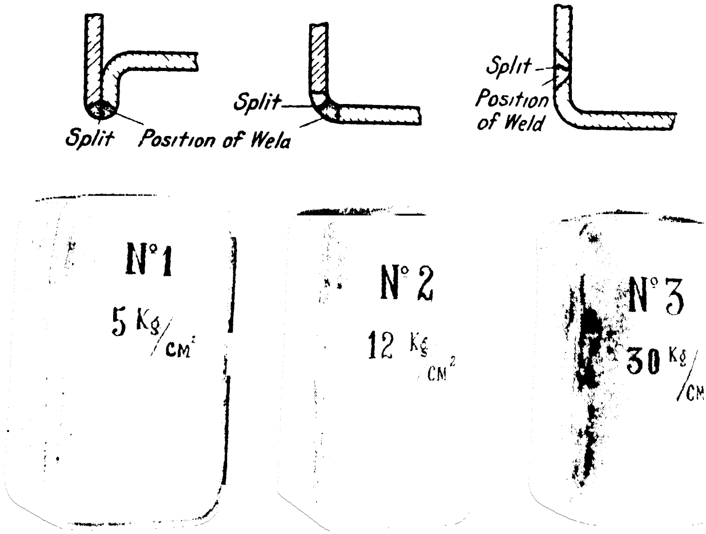


FIG. 135 STRENGTH OF DIFFERENT WELDED CONSTRUCTIONS OF SWITCH-OIL TANKS

(*above*) Sections of the welds (*below*) Welds split due to internal pressure

occurs and the switch is damaged. In switches of old types, it was the oil tank which would not withstand the pressure, as shown in Fig. 135.

(*b*) GAS EXPLOSIONS. When switching out takes place, the ball of gas formed may come to rest on top of the oil, before the oil piston has reached the cover of the switch. This occurs with switches in which the contacts are not sufficiently deeply immersed in the oil. In this case, burning may take place above the oil level. At each operation gases are formed which collect in the air space above the oil level. When the ratio between gas and air has reached a certain value the mixture becomes explosive and if, for any reason, a spark is formed simultaneously

—for example, a discharge spark on the bushing flange of an insulator—this may cause an explosion. Properly constructed switches should have the bushing flanges immersed in the oil below the oil level, so that discharge sparks in the space above are avoided.

A mixture of gases caused by previous switchings may, under some circumstances, be ignited without there being any external cause of ignition, due to the rapidly ascending hot ball of gas which is evolved by a heavy switching operation, particularly when the exhaust openings are too small or wrongly arranged. Modern switches should withstand without damage gas explosions arising from normal switchings and from gases ignited in the above way.

Switch defects traceable to pure gas explosions very seldom occur, and in most cases the trouble is caused by insufficient capacity of the switch tank to withstand pressure.

The most severe demand on an oil switch occurs when there is a steady arc under the oil, which is generally a result of defective insulation. In this case, the switch is stressed far above its pressure capacity and will certainly fail.

(*c*) SUBSEQUENT EXPLOSIONS After heavy switchings by oil-immersed switches the greatest care should be exercised before approaching or examining the apparatus. If too quick an attempt at examination is made, there is the danger of further explosion. This may take place because after heavy switching a quantity of gas always remains above the oil level. If the oil container is let down an explosive mixture of gas is formed with the outer air which enters, and this mixture, if ignited from any source, may cause severe burning of anyone in the vicinity. A sufficient interval should be allowed to elapse for the gases to be cooled and to escape before opening the switch. A very effective guard against this danger is a remote controlled device for draining the oil tank.

The danger of these subsequent explosions is particularly great in switch tanks with "relay chambers." The relay chamber is a closed space for housing instruments, control gear, and so on. It is connected by small openings with the oil container and in some cases contains also contacts for auxiliary circuits. When frequent operations are carried out at short intervals of time with such switches, switch-gases collect in them, which mix with the air of the relay chamber and may be exploded by the contact sparks.

There are also types of oil-immersed switches with which, in the "open" position, the breaker-contacts of the three phases situated on a common cross-piece are not wholly immersed below the oil, the contacts still carrying voltage. As these contacts are under voltage they may suffer a direct short circuit with a steady arc across a track on the cross-piece, along carbon which has accumulated due to heavy switching.

(*d*) Oil Throwing. In oil-immersed switches of old types serious defects sometimes occur due to badly arranged or too large vents in the cover, even if the switch itself is adequate for breaking the kVA. With heavy switchings, oil and carbon may be thrown out through these openings and settle on or between the terminals, causing short circuits between phases.

More modern switches have the vents, which cannot be entirely avoided, so arranged that the oil does not come out anywhere near the terminals but underneath.

With heavy switchings, it is impossible to avoid ejection of oil at these points. The openings protect the switch against too great a pressure rise and should on that account not be closed up. In switches having a high pressure capacity the openings may be made so small that even with very heavy switchings the loss of oil is limited to a few pints.

When erecting oil-immersed switches which are mounted on the floor, the shocks occurring as a result of switching out must be taken into account, since they have a tendency to lift the switch off its foundations. These shocks occur when the oil piston comes into contact with the cover. They are very powerful with high switching loads, and may exceed many times the weight of the switch, including its oil. Lifting forces of over 10 tons acting on the foundation bolts have been detected on heavy-duty switches for breaking capacities of over 1 000 000-kVA.

(*e*) Contact Distortion. When switching in on short-circuit, and also when there is a short circuit with the switch closed, there is a probability that "contact distortion" will occur. This results from the electrodynamic forces occurring at the moment of switching in, due to the heavy short-circuit currents which act on the contact parts. Burnt places may be left and the contacts may even be welded together. This distortion can be usually assigned to the two following causes—

1. The current path formed by the contact cross-piece and

the down rods tends to open, and as a result forces away the flexible cross-piece in a downward direction as in Fig. 136A.

2. The current first flows through one point on the contacts and afterwards moves to another path, as indicated in Fig. 136B. Since currents flowing in different directions repel one another this causes the contact to lift.

In modern switches special measures are taken to minimize this danger, such as the use of suitable finger and other types of contacts. In old types of switches the butt contacts can

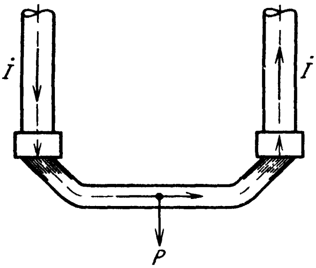


FIG. 136A OPENING FORCE, P, ON A SWITCH CROSS BAR DUE TO ELECTRODYNAMIC ACTION

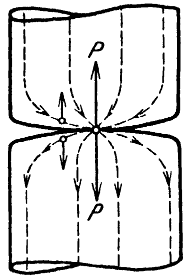


FIG. 136B OPENING FORCE, P, ON A SWITCH CONTACT DUE TO THE ELECTRODYNAMIC EFFECT OF THE PARALLEL CURRENT PATHS

often usefully be divided into several finger contacts, and at the same time the contact pressure raised.

(*f*) SWITCH RESISTANCES Another cause of switch trouble is the failure of built-in resistances, for example, buffer resistances to limit the switching-in current surge in transformers. Open-circuiting on such resistances may result in a permanent small arc, and wires or leads which have become loose may lead to flash-overs. If the switch fails to operate, resistances may remain permanently connected and burn out. Failure of mechanisms to operate when switching in and out has been responsible for many disastrous switch explosions. Efficient supervision and testing for such apparatus is therefore one of the most important requirements for the maintenance engineer. The mechanical troubles of switch operation are discussed in Chapter XXV, para. 5.

(*g*) BREAKING KVA. Many defects in oil-immersed switches are entirely due to wrong choice of switch. The switch may

have insufficient breaking capacity, or the protective relay may not be mounted in a suitable manner.

Adequate allowance should always be made for the highest possible switch-breaking capacity, particularly in plant where the load may increase from time to time. This is a factor of great importance to-day where increasing paralleling of power stations results in rapidly-growing supply systems It should be kept in mind that the demand on a motor switch is not fixed by the rated load of all the motors controlled by the switch or that portion of the plant which is connected to it, but by the greatest possible short-circuit load of all the generators connected in parallel when there is a short circuit behind the switch. Oil-immersed switches or switch oil tanks are particularly affected by the short-circuit forces released, since in this case the momentary highest short-circuit load has to be interrupted instead of the appreciably smaller steady short-circuit load, which only occurs after a few seconds. Motor switch tanks are usually dimensioned for the highest possible short-circuit load of the motor. If, however, a cable short-circuit develops between the terminals of the motor and the switch, this may give rise to a much higher short-circuit current. In all such cases where short circuits may occur in the cables between the switch and the consuming apparatus, an essential protection is to connect an oil switch in series with the operating switch. The latter should then only be equipped with a thermal protective device suitable for the connected motor, whereas the oil switch should have an instantaneous tripping device set to operate in case of a short circuit.

In arranging the selectivity of the switches, the shortest time of operation should be associated with the switch with the largest capacity, so that the short-circuit current, which is greatest when it first occurs, is broken by this switch.

The aim in practice to-day is to limit the effect of defects in oil switchgear. This is done either by building the switches in separate cells or by the even more satisfactory method of sinking the oil tank below the concrete floor of the switch house.

The satisfactory operation of oil switchgear can only be guaranteed when its behaviour on the heaviest short circuits likely to occur in operation is experimentally checked. The leading manufacturers have built special short-circuit testing plant to provide proper testing facilities for oil switches.

3. Isolating Switches. (*a*) Wrong Operation. If isolating switches are wrongly used, for example, drawn while under load, serious damage to the switchgear will result. Very often there is such a serious outbreak of fire as to necessitate the use of extinguishers. The operator of a switch should always, before withdrawing it, be prepared for trouble and re-close the switch immediately on the appearance of a dangerous arc. In this way it is possible to avoid serious damage. Isolating knife switches are generally not constructed for operation on load and they should always be locked. An electric arc resulting from withdrawing the switch while carrying current is not provided for, either electrically or mechanically, and consequently it develops in an uncontrollable way, and may spread to adjacent conductors or flash over to earth.

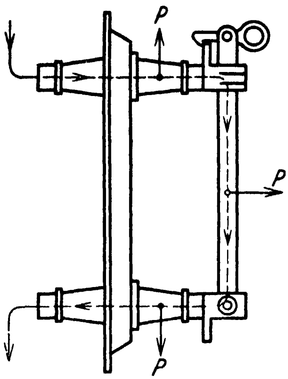


Fig 137. Electrodynamic Forces, P, Acting on a Switch Blade and Insulators of an Isolator

(*b*) Throwing Out. In addition to wrong operation of isolating switches as discussed above, these may be opened for another reason. As a result of unsuitable arrangement of the leads to an isolating switch, when a short circuit occurs, due to the electrodynamic effect in the contacts there are appreciable forces tending to open the switch blade. This may consequently be thrown out as shown in Fig. 137. To prevent this, the switch blades should, whenever possible, be placed so that the direct pull of the circuit holds them in place. The opening of a switch by itself is shown in Figs. 138A and 138B. This failure was produced experimentally and it was shown that in the case of Fig. 138B the switch opened with 65 000 amperes and for Fig. 138A the incomplete opening was with 45 000 amperes. Both illustrations also show clearly the changes of direction in the current path giving rise to mechanical forces which act on the switch blade.

In addition to the forces which open switch blades, other forces occur which may reduce the contact pressure according to the isolator construction. Particularly with isolating switch blades which are bolted to prevent their automatic opening, there may be sideways movement of the contact

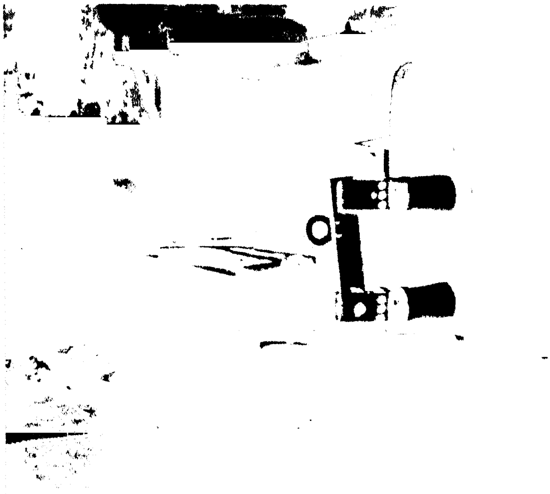


FIG. 138A OPENING OF AN ISOLATOR DUE TO ELECTRODYNAMIC FORCES AT 45 000 AMPERES START OF PROCESS

FIG. 138B OPENING OF AN ISOLATOR DUE TO ELECTRODYNAMIC FORCES AT 65 000 AMPERES. SWITCH FULLY OPENED

as in Fig. 139, causing sparks and damage to the apparatus unless the isolating switch is specially protected against this. In the isolating switch in Fig. 140 this phenomenon has occurred during the passage of about 50 000 amperes. This switch was equipped with bolts to prevent its automatic opening In more modern designs not only are the contacts protected against burning, but special care is taken to prevent the breaking of the insulators at the same time, since the

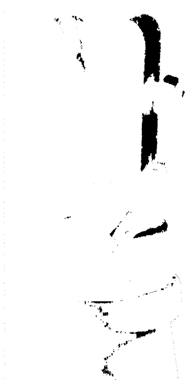


FIG. 139 ISOLATOR WITH SIDEWAYS CONTACT MOVEMENT

(The switch blade was bolted to prevent a heavy current forcing it open.)

FIG. 140 ISOLATOR WITH SIDEWAYS CONTACT MOVEMENT DURING THE CURRENT SURGE

opening force obviously has also to be carried by these Experiments have shown that ordinary knife switches with short-circuit surges of 20 000 amperes are generally thrown out. Isolating switch blades with a suitable protective device against automatic throwing out and against contact movement have withstood short-circuit currents up to 100 000 amperes.

(*c*) SWITCHING OUT TRANSFORMERS ON NO-LOAD With suitably designed and constructed isolating knife switches, transformers up to certain sizes can be switched out at no-load with safety. On the other hand, for operating voltages over about 100 kV. transformers on no-load are very seldom isolated on account of the excessive arc length. When using air-break switches out of doors, the direction of the wind should be taken

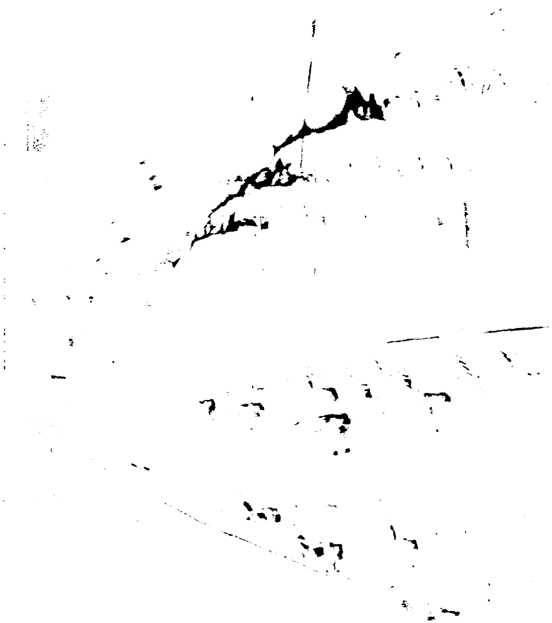


Fig. 141a. Arc on Isolating a 1 500 kVA., 50 kV. Transformer on No-load

Fig. 141b. Arc on Isolating a Transformer for 2 000 kVA., 8 kV. on No-load

into account since in bad cases flash-overs between phases are almost unavoidable. When isolating wattless overhead supplies, approximately the same arc lengths occur as in the case of transformers on no-load of similar current loading. When opening the isolating switch, special care is necessary on account of excess voltages occurring. Figs. 141A and 141B show the arcs arising when isolating a transformer on no-load. It is an advantage to operate the isolating switch so that the contacts are opened with the maximum possible speed, which somewhat reduces the arc length. With slowly operated switches when overhead supplies are to be isolated, excess voltages occur due to re-ignition of the arc. Such excess voltages are much less likely to occur with oil immersed switches.

CHAPTER XXVII

MEASURING APPARATUS

1. Meters. Electrical meters are subject to very diverse troubles, which may arise in connection with their design, type and degree of precision, their fixing and their use. The causes of trouble can be divided into those arising in the meter itself and those due to the effect of environment on the meter. Of the numerous possible internal meter troubles, one need only mention bearing friction, errors in calibration due to insufficiently balanced rotating parts, errors in the scale, bent pointers, sticking pointers and all internal results of overloading.

In this chapter reference will only be made to a few of the general external causes of trouble affecting operating instruments and also portable measuring apparatus. Paragraph 31 of the Verband Deutscher Elektrotechniker regulations for meters distinguishes two classes G and H of operating instruments, and defines their degree of accuracy as in the following table, in percentages of the full measuring range.

Type of Instrument	Class G	Class H
Current, voltage and load meters for direct and alternating current	± 1·5%	± 3%
Power factor meters	± 2 %	

The permissible error for an ammeter of Class G with 15 amperes range and a scale divided into 150 sections is therefore ± 2·2 scale divisions or ± 0·22 amperes. The same deviation in scale divisions is also permissible for the smaller readings. The measuring range of an instrument should on this account be so chosen that the highest value to be measured gives a full-scale deflection. The corresponding British practice is covered in B.S.S. 89, in which, however, only one grade of instrument is recognized, and the permissible errors are generally similar to those for class G above.

Large errors often arise from rubbing the glass face of a meter with a cloth, as a result of which the glass is electrically

charged. This can be cured quite simply by damping the glass by breathing on it.

(*a*) MOVING COIL INSTRUMENTS. These are used for measuring direct current and voltages and have a construction similar to that of the model instrument illustrated in Fig. 142. Between the soft iron pole shoes of the permanent magnet there is a powerful magnetic field. The main portion of this magnetic flux passes directly from one pole across the air gap, where it cuts the moving coil carrying current to be measured through the central soft iron cylinder to the other pole. A small part of the flux, the "leakage field" extends outside this path between the back surfaces of the poles in an arc through the air. This leakage field may affect adjacent similar instruments (particularly precision instruments) if they are very near. The influence, however, is so small as to be of little moment in switchboard instruments of modern construction.

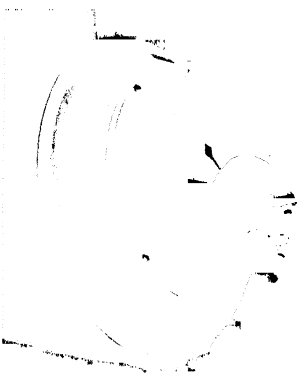


FIG. 142 MOVING COIL INSTRUMENT

On the other hand, moving-coil instruments on switchboards may be directly influenced by the magnetic fields of nearby direct current conductors, such as bus-bars or cables, which affect the coil and disturb the reading. In addition, such external fields if they are very strong are able to alter permanently the field of the permanent magnet so that the meter requires complete overhauling. Less often it may happen that strong alternating currents with their alternating magnetic fields pass near the permanent magnet, and due to the continuous magnetizing and demagnetizing tend to weaken it. Any test results are useless if this type of influence is affecting the switchboards or measurements.

(*b*) MOVING-IRON INSTRUMENTS FOR DIRECT AND ALTERNATING CURRENT. With these types of instruments, which are very common on switchboards and will withstand heavy overloading, a coil induces a magnetic field flowing chiefly in the air, which exerts a pull on a movable iron armature. Troubles may therefore arise, with both kinds of current, from

external stray fields which predominate over the meter field and cause incorrect readings. Screening from external fields by an iron housing is possible, especially for alternating current instruments, but disturbing direct currents may lead to the formation of poles in the screen.

(*c*) HOT-WIRE INSTRUMENTS FOR DIRECT AND ALTERNATING CURRENT. The characteristic weakness of this type of instrument is the great danger from overloading, when the wire may be easily burnt out. Since the position of the pointer is fixed by the temperature of the wire, the reading is dependent on the ambient temperature. The effects of variation in this temperature can usually be observed by alterations in the zero of the instrument to correspond with high or low room temperatures. Modern types of this apparatus guard against this trouble by providing temperature compensation, or else a high working temperature of the hot wire.

FIG. 143 ELECTRODYNAMIC INSTRUMENT (WATTMETER)

Strong external magnetic fields may affect hot-wire instruments, since the hot wire becomes a conductor placed in a magnetic field. Very brief current surges—for example, sudden loads—cannot be measured by this type of instrument on account of their thermal time lag.

(*d*) DYNAMOMETER-TYPE INSTRUMENTS FOR DIRECT AND ALTERNATING CURRENT. These may be divided into two classes, those constructed without iron and those with iron casings. Fig. 143 shows one of the former type.

In the case of open dynamometers the fields of both systems are entirely in air. On that account, the weaker their self-excited fields, the more are they subject to the influence of external fields. In alternating current instruments, trouble may be caused by a magnetic field of the same frequency, but not by a steady external field. In wattmeters the error, particularly with a low power factor, may be very considerable.

The magnetic fields of the fixed and moving coils in the closed type of instrument flow mainly in an outer shell and in

the core. The inner fields are usually quite strong, and external fields tend on this account to have little effect on the moving coil. Magnetic troubles are, for similar constructions, the same as for d.c. moving coil instruments.

Dynamometer-type wattmeters may be damaged by being wrongly connected as in Fig. 144 (*b*). Between two coils there

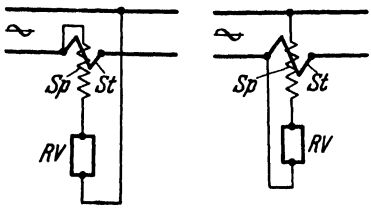


FIG. 144. CONNECTION OF A SINGLE-PHASE WATTMETER
(*a*) Correct. Small voltage between current and voltage coils.
(*b*) Wrong. Supply voltage between current and voltage coils
St = Current coil. *Sp* – Voltage coil. *RV* – Series resistance of the voltage coil.

should be the lowest possible voltage to prevent internal flash-overs along creepage paths.

(*e*) ROTATING-FIELD (FERRARIS) INSTRUMENTS FOR ALTERNATING CURRENT, VOLTAGE, AND MORE ESPECIALLY POWER. The torque is the outcome of the electromagnetic forces between the magnetic alternating field and the eddy currents induced by it, which circulate in a solid aluminium disc. The recording of this type of instrument is dependent on the frequency. The ambient temperature influences the reading considerably, also the heating of the aluminium disc with continuous loading. External causes of trouble are practically non-existent.

(*f*) POWER FACTOR METERS OF OPEN AND CLOSED TYPES. In the most generally used crossed-coil type, a voltage coil rotates in the field produced by a fixed current coil. In power factor meters, especially registering instruments, the reading is not reliable for current strengths below 20 per cent of the rated current, since the motive force is too small. These instruments are affected just as are open and closed dynamometer type instruments. Permanent magnet fields and the fields of heavy current conductors should be kept at a distance from both instruments.

(*g*) TESTING FOR CAUSES OF TROUBLE. A simple test for instruments is to verify if the pointer with the instrument

disconnected rests accurately on the zero of the scale. If disturbing influences are suspected, they should be removed; for example, an adjacent conductor switched out or a nearby instrument or iron parts taken away At the same time the deflection on the instrument should be noticed. Finally, an instrument may be tested by removing it from its usual place on the switchboard after the attachment of long temporary leads and testing its deflection again under otherwise similar conditions. In such cases, careful consideration of all the possible disturbing factors is necessary.

Internal defects of instruments can generally only be repaired by experts.

As a general guide to the use of instruments, it should be kept in mind that all their current leads both to and from, and also any adjacent leads carrying heavy currents should, as far as possible, be placed close together. (See Chapter XXXI, para. 1.) They should also be so arranged with respect to the instruments that their influence on the latter is as small as possible. It is important that instruments are only used in their own working position on the switchboard, since their moving system is generally specially balanced for this position. When connecting such apparatus as load meters and power factor meters, care must be taken that the leads and terminals are correctly connected together. Diagrams of connections should be used but it is advisable to check these first.

2. Potential Transformers. Sometimes potential transformers are provided with fuses on their secondary side. When these blow unnecessarily the supply may be cut off, particularly if protective relays are supplied by the potential transformer. (For example, in Fig 160, with blowing of the middle fuse at *b*.) In the reverse-power relay a blown potential transformer fuse causes an altered phase-angle of the magnetizing current in the voltage coil, as a result of which the relay operates and eventually trips the circuit. The same trouble in the case of a voltage regulator produces a corresponding effect to a sudden voltage drop, and the regulator consequently endeavours to raise the voltage, exciting the generator up to the highest possible value. This causes heavy circulating currents between machines running in parallel, or in the case of a single generator, a large increase in voltage. With synchronizing devices such defects in protective gear may result in incorrect paralleling. For this reason it is

better not to apply protective devices on the secondary side of potential transformers when these supply protective relays or regulators. Sufficient protection for the transformer itself is given by the primary relays. In the design and lay-out it is important to ensure that when fuses blow, no short circuits of the bus-bars or breakdowns to earth are caused by the arc.

Nowadays suitable primary fuses are employed with series resistances which appreciably reduce any chance short circuit on the terminals of the transformer, and at the same time limit the short-circuit arc. Defects in the transformer ratio through this series resistance hardly ever occur if the resistance is suitably chosen.

3. Current Transformers. There are three common causes of failure of this apparatus--

1. The transformer gives wrong values, that is, it has an incorrect ratio of transformation.

2. It is not protected against heavy short circuits and may be damaged by such.

3. Flash-overs may occur due to insufficient insulation and the effects of overheating.

The defects arising in connection with the third group have already been mentioned in Chapter XX, since they are common to both current and power transformers.

(*a*) ERRORS IN TRANSFORMATION RATIO. When tracing a ratio of transformation error, the starting point is to check the actual load and compare it with the value shown on the meter. It should be remembered that the ratio of transformation of a current transformer will only be accurate up to a certain loading within the range for which it is designed. The secondary loading varies with constant primary current according to the impedance of the secondary circuit. Fig. 145 illustrates the secondary loading in voltamperes and the transformation ratio relative to the secondary load impedance when a constant current flows on the primary side. It can be seen that the transformer ratio from a certain load upwards becomes greater, since the secondary current decreases, although the primary current remains the same. This phenomenon is caused by the increase in magnetic flux with increasing secondary voltage, so that a stronger magnetizing current has to be handled.

When trouble has developed on current transformers supplying relays and instruments in addition to an ammeter or wattmeter, it is often found when the current transformer

is tested that it appears accurate according to the calibrating standard, that is, when an ammeter only is used for loading. The defect first appears when the apparatus in operation is connected to it. Since, then, the voltage across the secondary windings of the current transformer is higher, if the winding insulation is somewhat weak a flash-over may occur which the small test loading does not bring to light.

In addition to the transformation ratio in current transformers with precision accuracy, the checking of the phase-angle of the currents is important. By phase-angle is to be understood the angular deviation in minutes of an arc of the secondary current vector from its true place, i.e. 180° opposite to the primary current. The influence of the phase-angle occurs particularly when measuring inputs to motors and transformers on no-load, since then very low power factors occur. It is obvious that at low power factor an angular deviation of the secondary current has more influence on the effective components than if the measuring is being done at unity power factor.

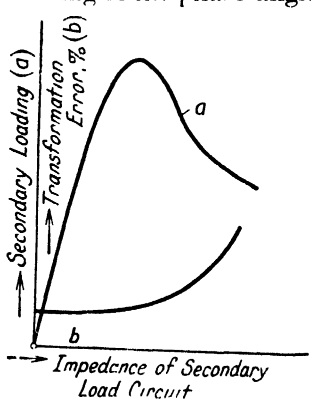


Fig. 145. General Characteristics of Current Transformer with Constant Primary Current

Excessively large variations of the phase angle may very likely be caused by defects in the protective resistances. These are intended to protect the primary winding from damage on the occurrence of short circuits. Further details regarding defective protective resistances can be found in this chapter, para. 3 (*c*).

Small variations of the transformation ratio may result from the polarity test, which may be carried out either by the manufacturer or by the official testing bureau. For this the connection shown in Fig. 146 is usually employed. To determine the winding polarity the current transformer is supplied with direct current, and the deflections of a voltmeter connected to the secondary winding are observed when opening and closing the primary switch. This means that the core of the transformer has some magnetic remanence after the test corresponding to the flow of the direct current. On this account it exhibits with

a subsequent alternating current test certain errors in the transformation ratio and in the phase angle. The remanence is best removed by supplying the transformer with alternating current from a separate generator, the frequency of which is gradually reduced so that the alternating current strength and frequency approach zero.

(*b*) SHORT-CIRCUIT STRESSES. The characteristic of current transformers when used in conjunction with other parts of electrical plant such as generators, motors and power transformers is that under some circumstances they may have to withstand abnormally high short-circuit currents. These short-circuit conditions frequently are the most severe on circuits containing auto-transformers.

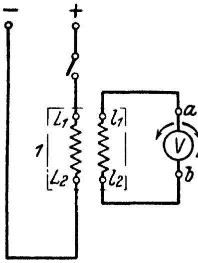


FIG. 146. TEST FOR POLARITY WITH DIRECT CURRENT ON CURRENT TRANSFORMER
(1) Current transformer.
(2) Polarized voltmeter.

All other types of apparatus limit either directly or indirectly, by means of their short-circuit impedance, the magnitude of the currents occurring in them due to supply short circuits. Since the impedance of a current transformer must be as small as possible, it has practically no influence on the magnitude of a short circuit arising in its load circuit.

According to where the current transformer is placed in the system, short-circuit currents of different strengths may have to be carried by it. The stress on a transformer is determined by the ratio of the highest short-circuit current occurring to the normal current. This ratio increases the smaller the normal current is when compared with the capacity of the supply. It is obvious that this ratio is also dependent on the distance of the transformer from the power station.

In the system shown in Fig. 147 the following short circuit stresses can be calculated at the assumed place of short circuit, neglecting the cable impedances.

Normal current of generator	3 000 A.
Transient short-circuit current of the generator $15 \times 3\ 000$ A.	45 000 A.
Steady short-circuit current of the generator $1{\cdot}6 \times 3\ 000$ A.	4 800 A.
Normal current of the current transformer . . .	100 A.

Transient short-circuit current

$$\frac{45\,000}{100} = 450 \times \text{normal current of transformer.}$$

Steady short-circuit current

$$\frac{4\,800}{100} = 48 \times \text{normal current of transformer.}$$

The transformer is liable to be damaged both from heating and mechanically by these high currents. The highest permissible short-circuit current is chiefly fixed by the rating of the transformer at normal current. For most current trans-

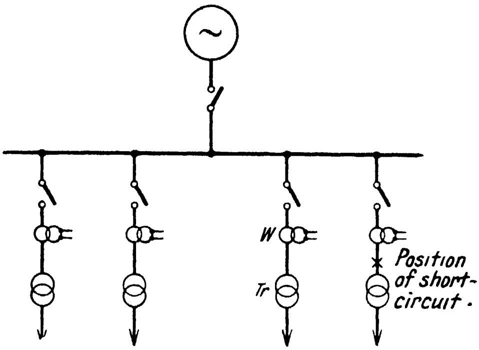


FIG. 147. DIAGRAM OF CONNECTIONS USED FOR CALCULATING THE SHORT-CIRCUIT STRESS ON A CURRENT TRANSFORMER.
Tr Transformers. *W* Current transformer.

formers, according to the design, its value may be over 100 times normal current, assuming a short-circuit time of about 1 sec.

The ability of a current transformer to withstand magnetic forces is obviously entirely dependent on its construction. It is, however, generally smaller in the case of transformers of an accuracy corresponding to the official specifications than in transformers where less precision is required, chiefly because the former necessitate a larger number of winding turns than the latter. "Through" type current transformers of the usual construction and with small normal currents have not the precision required by the official specifications, since they are simply arranged round the conductor and consequently have only a single primary turn. This type of instrument is, however, entirely satisfactory under short-circuit conditions.

Breakdowns sometimes occur with short circuits, even

though the current transformers are made thermally and electrodynamically to withstand these short circuits. Due to the high current, a comparatively high voltage occurs, mainly between the primary leads, which may puncture the insulation. The resistances placed in parallel with the primary winding as a protective device may be damaged, especially when they are not well mounted, have bad terminal connections, or are dirty. Many manufacturers use protective resistances made of silicon carbide. Since, however, on the one hand, the resistance of these is closely dependent on the voltage, and, on the other hand, when they are subjected to the sudden stress caused by a short circuit, flash-overs along the outer surface may occur, in certain cases metallic resistances are more suitable, especially when low ohmic resistances are necessary.*

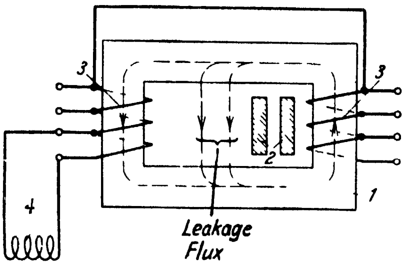


FIG. 148 BAD WINDING ARRANGEMENT ON CURRENT TRANSFORMERS

(1) Iron core
(2) Primary current bus bars
(3) Secondary winding with tappings
(4) Load

With heavier loading of the current transformer and on the occurrence of short circuits, breakdowns between turns in the secondary winding naturally occur much more readily than with lower loading. In the first case, the winding voltage is correspondingly higher, and since the winding moves during the short circuit, it is damaged more easily by the higher voltage. In current transformers of old designs, very long coils are usually found which behave in a much less satisfactory manner in case of short circuit.

With high-current transformers having tappings for different transformation ratios, very high voltages may arise. The highest voltage occurs between the open secondary terminals of the unloaded portion of the windings, and reaches a maximum at the highest primary current, and when the secondary loading is connected between the lowest tappings to give the lowest transformation ratio, as in Fig. 148. This is partly due to the primary lead, 2, being unsuitably arranged in the opening of the core and partly to the distribution of the

* Berger. *Bulletin Schweiz. Electrotechn. Vereins*, 1927, Book 2.

secondary winding on both legs. It is generally possible to effect an improvement by distributing the primary current bus-bars over the whole of the gap of the core. A fundamental improvement is also achieved by distributing secondary windings between tappings on both legs.

(c) Insulation Defects. A reliable earthing of the secondary winding of a current transformer on the transformer itself should always be provided, to avoid internal discharges and damage to connected instruments and apparatus. When repairs are to be undertaken, or when changing instruments during operation, the transformer should be protected against its secondary winding being open-circuited, since this would be a source of great danger to the workmen. In modern equipment a simple short-circuiting device is available for this purpose and should be provided on the transformer before it leaves the manufacturer.

In oil-immersed current transformers insulation defects may be a very serious matter, since they may result in an explosion of the tank. The gases formed by sparking under the oil may be mixed with air above the oil level and explode or cause too great a pressure, in exactly the same way as in the case of oil-immersed switchgear. Any phenomena suggestive of this process should, therefore, receive careful attention. The periodic checking of the oil level and the condition of the oil are very important with high-voltage current transformers.

CHAPTER XXVIII

STARTING AND REGULATING APPARATUS

MANY of the troubles met with in starters are traceable to contact defects which are described in Chapter XXV, paras. 2 and 3.

1. Controllers. On controllers, faults occur particularly with switching operations, generally reversing (altering the direction of rotation of motors) and changing the grouping of motors, for example, from series to parallel connection, and vice versa. On a.c. controllers with this operation there is the danger of short circuits between phases, with d.c. controllers breakdowns between poles, and in the case of traction controllers breakdowns to earth. Fig. 149 illustrates the occurrence of a short circuit due to the drawing out of arcs. The cause is in most cases the same. When switching over, one circuit must first be broken before it is connected again with reversed polarity. From the mechanical point of view the switching over is generally correct, since mechanical interlocking is used to ensure this. The arc, on interruption of the circuit, however, requires a longer or shorter time to extinguish itself according to the magnetic conditions. There is thus a danger that it will continue to burn at the place where the circuit is broken and result in a short circuit if the circuit is immediately closed again. The troubles occurring at the instant of reversal or of change of grouping are generally solved by testing, bearing this in mind.

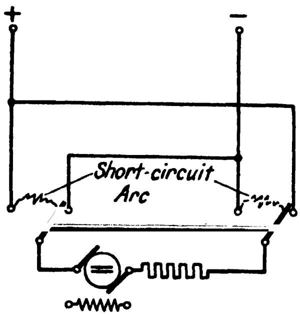


FIG. 149. FORMATION OF A SHORT CIRCUIT WHEN REVERSING A MOTOR

Controllers on certain drives, particularly cranes, rolling mills and similar duties, must withstand very severe conditions due to the continual reversals. At the same time they must be well protected against dust and dirt, which again usually results in their being insufficiently ventilated. The switch gas evolved as a result of the continual switching cannot escape and on

this account may cause flash-overs. Loss of material due to burning of contacts is discussed in Chapter XXV, para. 3.

Controllers, especially for traction purposes, should be easily operated, since if this is not the case the apparatus and consequently the vehicle is not properly under the control of the driver. Too much force has to be exerted to move the controller into the desired position, with the danger that it may be pushed past the proper place. If the switching mechanism is too stiff, there is the additional danger that the contacts do not engage properly, and they may have too little pressure. The troubles arising from this are described in Chapter XXVI, para. 2 (*c*). A good traction controller should operate so easily that if placed in a position between two steppings it falls by itself into one of these steppings.

2. Air-cooled and Oil-immersed Starting Resistances. Air-cooled starting resistances may become defective as a result of too high a temperature, oxidization, and unsuitable material, for example, iron resistances. Other materials, for example, brass, are subject to short circuits between different resistance groups, since the resistance grids may become distorted and come into contact with one another. Attention should always be given to adequate spacing of the resistances.

Careless manufacture may result in invisible material defects such as cracks, particularly at bends, which in service lead to apparently inexplicable failures. This is especially likely on resistances exposed to continuous vibration, for example, on crane or traction service. Resistances of various kinds of cast iron are particularly sensitive in this respect and need reliable supporting devices.

Often maintenance staff, due to lack of instruction, are disturbed by the apparently excessive temperature of resistances. On resistances of nickel-iron alloy the rise in temperature of the outlet air at a distance of about 5 cm. may reach 150° C. without there being any cause for worry. This corresponds to a temperature of the metal itself of about 300° C. Obviously this temperature depends on the ambient temperature and the facilities for escape for the heated air. Dust and dirt are also a source of trouble in this kind of apparatus. In exceptional cases when continual repair is necessary, it often pays to reconstruct the apparatus or to replace it by an oil-immersed resistance. When using oil-immersed types, the troubles associated with the lubrication of

mechanical parts and contacts do not arise and the insulation is improved.

The starting resistances of motors frequently burn out as a result of being left in the starting position, or between two positions. When starting up a.c. motors vibrations often occur caused by a bad contact in the resistance of the rotor starter, so that the resistance values in the three phases are very unbalanced.

3. Liquid Starters. Liquid starters use tap water or distilled water as resistance material and galvanized iron or bronze for their electrodes. They are only suitable for use with alternating current, since various electrolytic processes and the danger of the production of mixtures of oxygen and hydrogen gas prevent their use with d.c. apparatus.

These starters are mostly used in conjunction with large a.c. motors. When used solely for starting the motors, they are usually short-circuited in the final position by a built-in switch. Water resistances are specially suitable for motors in which a certain energy has constantly to be absorbed in the rotor starter and the resistance must be adjustable, for example, in the slip regulation of motors for driving conveyors, rolling mills, and the like. The starter in these drives not only serves to set the motor in motion and to control it, but in addition, in conjunction with a flywheel, prevents the occurrence of excessive peak loads on the a.c. supply. These starters are generally provided with a cooling device for the electrolyte which is either built directly into the tank or else mounted outside.

The resistance values of a liquid starter in each position can be deduced from its main dimensions, depth of immersion, surface and distance apart of the electrodes, and the electrolyte resistance. The adjustment of the resistance for the motor is, according to the design of the starter, carried out by regulation of the water level, and by varying the electrolyte resistance by the addition of soda.

A curve illustrating the alteration of the water resistance with increasing proportions of soda is given in Fig. 150. To reduce the resistance, a smaller soda content than is normally employed should be adopted; and excess in this direction frequently causes trouble. An addition of soda amounting to about 0·1 per cent of the weight of water reduces the starting resistance of the water by about 50 per cent.

In rotor starters with variable water level the effective electrode surface is regulated by altering the depth of immersion. If this is too small, there is the danger of flashing over, generally on switching in with a high rotor voltage. When the plates are insufficiently immersed, particularly with high voltages, sparking occurs on the electrodes accompanied by considerable rattling on account of the too great concentration

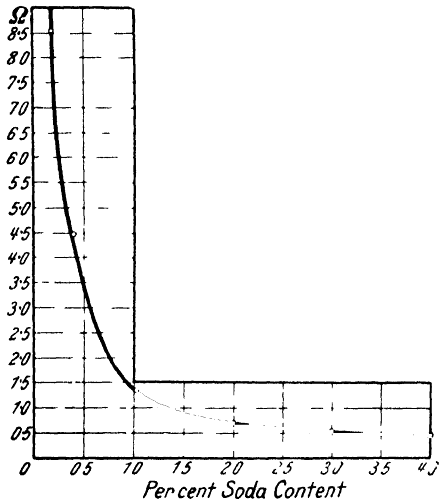


FIG. 150. VARIATION IN RESISTANCE OF A LIQUID STARTER WITH DIFFERENT AMOUNTS OF SODA IN THE ELECTROLYTE

(Soda content in percentage weights.)

of current. The electrodes may become so overheated as to be partially melted.

The resistance ratio

$$\frac{\text{Highest resistance at the start}}{\text{Lowest resistance at the end}}$$

of the water resistance used as a rotor starter should be at the outset as large as possible, since otherwise the addition of soda cannot effect any reduction. To be successful the resistance should then be so fixed that in the starting position the current on switching in is not too great. On the other hand in the final position, at the lowest resistance value, the motor speed should be sufficiently high to prevent too high a current surge when the resistance is short-circuited. The starting value

fixes the switching in surge, and the final value determines the slip of the motor before the short-circuiting of the starter, and the resultant surge.

When adding soda, it is customary to use chemically pure soda, dissolved in a small quantity of hot water, and to mix the concentrated solution thoroughly with the electrolyte

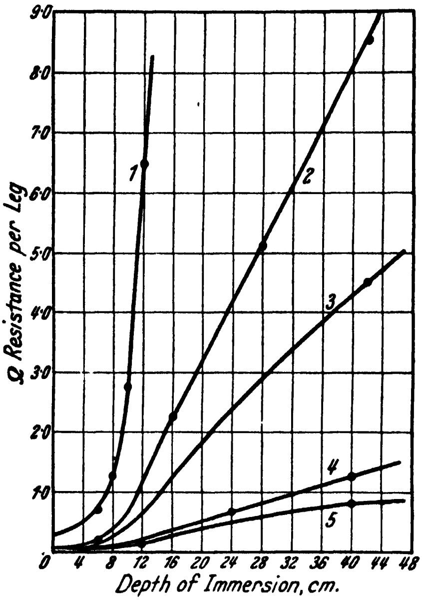


FIG. 151. RESISTANCE OF A LIQUID STARTER RELATIVE TO THE DEPTH OF IMMERSION WITH DIFFERENT AMOUNTS OF SODA IN THE ELECTROLYTE

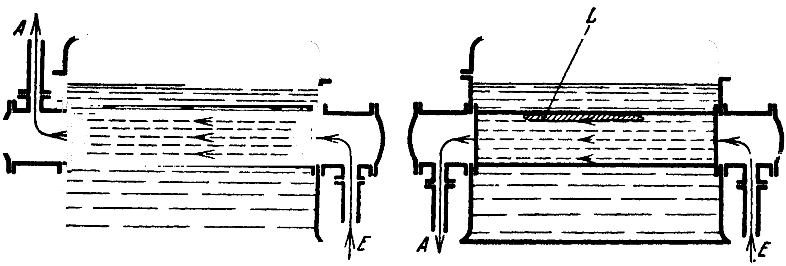
(1) Pure tap water.
(2) ,, ,, ,, + 0·2 per cent soda } 20° C.
(3) ,, ,, ,, + 0·4 per cent soda } 20° C.
(4) ,, ,, ,, + 1·0 per cent soda } 20° C.
(5) ,, ,, ,, + 1·0 per cent soda, 60° C.

before switching in again. It must be kept in mind that the conductivity of the electrolyte is improved due to the temperature rise, which will be about $2\frac{1}{2}$ per cent per ° C., with average soda content. The variation of the resistance with depth of immersion is dependent on the shape of the electrodes. Good ratios are given by designs having separate resistances for each phase, which can be achieved by using porcelain tubes, for example. Fig. 151 shows the resistance curves of such

a starter with different amounts of soda and at various temperatures.

Damage to the inner surface of the water tank is generally traceable to corrosion. In such cases the container should be cleaned by scraping off the deposits and painting the surface with red lead and asphalt.

A particularly destructive factor is chlorine contained either in the water or the soda. which affects the electrodes and sometimes the tank. If there has been a considerable loss of the surface of the electrode material due to corrosion, or if there are marked deposits of chalky matter, the final resistance of



(a) (b)

FIG. 152. LIQUID STARTER WITH WATER COOLING
(a) Proper connection of the cooling piping. (b) Wrong connection of the piping.
E = Inlet for cooling water. A = Outlet for cooling water. L = Air pocket.

the starter may be too large and the current surge on short-circuiting the starter may be very excessive.

The coolers of liquid resistances may, for the following reasons, become corroded away. A horizontal cooler in which the inlet and outlet pipes are connected on the underside of the upper part of the cooler tends to fill with air which is driven out of the heated cooling water. If, on the other hand, the cooling water inlet is below and the outlet above, the cooler works properly. Figs. 152 (*a*) and (*b*) make this point clear.

If the tubes of the cooler are covered with a chalky deposit, the water conducts away insufficient heat (see Chapter XXXVII, para. 6). A periodic cleaning by a 3 per cent solution of hydrochloric acid is to be recommended, and provision should be made for the escape of the gas evolved. The cooling tubes should afterwards be thoroughly washed with clean water. Water containing salt, acid, large quantities of lime or organic

impurities is not suitable for use in coolers. Liquid starters will withstand overloads of very brief duration with very little damage. If the load capacity is exceeded, however, it is soon evident, as the water boils over. If, therefore, suitable outlet openings are provided on the top of the tank, it minimizes the risk of explosion. After overloading of this type, the water level should be checked and the loss made good to render the starter fit for further service.

CHAPTER XXIX

CONTACTOR GEAR

General Troubles. In addition to the general contact defects already mentioned in Chapter XXV, the following typical faults occur on such parts of contactor gear as contactor relays, overload trips, and so on: uncertain switching-in and -out, "locking in" and humming of the magnetic system.

(*a*) IRREGULAR OPERATION OF CONTACTOR MAGNETS. Uncertain switching-in may occur due to defective mechanical terminals as a result of oxidization or accumulation of dirt, or from general deterioration. With direct current relays which have to operate comparatively frequently, an *economy resistance* circuit is often employed. With this, the magnet coil has a higher voltage for closing than it afterwards has for holding in the contactor. A resistance is connected in series with the magnet coil, which when not under voltage and during the closing is short-circuited by a contact on the relay itself. Only at the conclusion of the movement does this contact switch-in the series resistance. If this takes place too soon, the magnetic pull of the coil is too weak to overcome the mechanical resistance occurring in the last phase of the closing movement on the contactor system. The magnet armature then falls back, and afterwards is again attracted, the process continuing, when it is said that the contactor "flutters."

Relays and overload trips have often to operate with certainty and close with an operating circuit contact of quite short duration, and then be held by a retaining coil as shown in Fig. 153. This may arise, for example, with automatic paralleling devices. With unsuitable designs failures often occur on switching-in, when the mass of the relay to be accelerated is too large and on that account requires the auxiliary contact to be closed for a longer interval of time than is available. In addition, the retaining winding may be too weak, particularly if the current rise in the circuit, as a result of excessive inductance, is slow. The polarity of the series coil may, moreover, be reversed. The two coils are then opposing one another in their magnetic effect instead of aiding one another.

When connecting a direct current magnet coil on different supply voltages as in Fig. 154, a strange and unaccountable phenomenon may be observed, in that the magnet works properly at the higher voltage but not at the lower voltage; although, by means of suitable series resistances, it is provided that when connected on the higher voltage as at (*a*) the magnet coil, when in continuous operation, has exactly the same terminal voltage as with direct connection to the low voltage (see (*b*)). The theoretical explanation of this phenomenon is

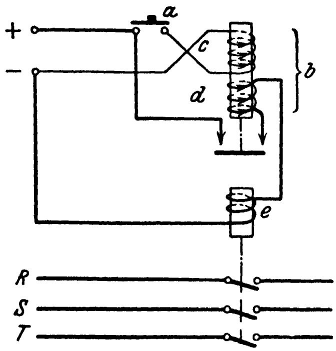


FIG. 153. DIAGRAM OF CONNECTIONS OF A SWITCH CLOSING RELAY WITH SERIES RETAINING COIL

(*a*) Operating contact.
(*b*) Switch closing relay.
(*c*) Relay voltage coil.
(*d*) Relay series coil.
(*e*) Main switch solenoid.

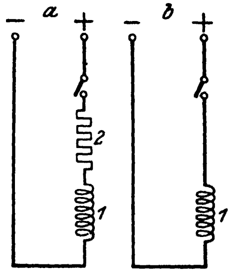


FIG. 154. CONNECTION OF A D.C. MAGNET COIL

(*a*) On high voltage with buffer resistance.
(*b*) Directly on to low voltage with resulting poor magnetic pull.

simple. In a d.c. circuit with ohmic resistances and inductance, the rise in current is as shown in Fig. 155. It can be seen from this that the current rise to begin with is hardly influenced at all by the ohmic resistance of the circuit. It is fixed solely by the ratio terminal voltage/inductance. With the above connections, the value of the inductance is the same in each case, although the supply voltage in one case is higher, for example, 220 volts, and the coil attracts immediately. At 110 volts terminal voltage and with the current increase slowed down to a half, the magnet may not, however, pick up sufficiently quickly. The operation of a direct current magnet may be dependent on the time taken for the increase in coil current after switching in. Variations of these ratios may lead to this

type of failure, for example, in magnets which were originally provided by the manufacturer with series resistances, but subsequently are operated directly on low voltage. The conditions described are freely used in control practice when switching in a d.c. circuit, as described in Chapter XXXIII, para. 1, for example, for the voltage regulation of generators to hasten the building up of the magnetic field.

Irregular opening of contactors occurs, principally on direct current, from the effects of residual magnetism. As a protection

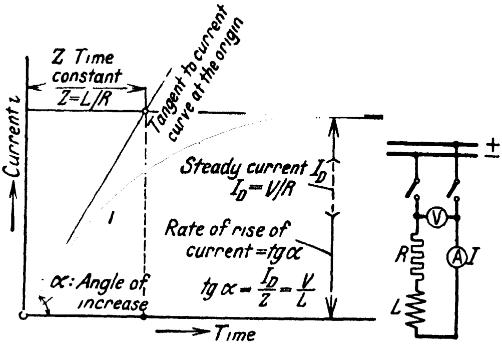


FIG. 155. SWITCHING-IN CHARACTERISTICS OF A D.C. CIRCUIT WITH RESISTANCE R AND INDUCTANCE L

Relation between rate of current increase and the supply voltage and inductance.

against this, an air gap is always provided in the magnetic circuit which may be in the form of a brass insert. Relays and overload trips which in service have to operate in an inclined position must be specially constructed for the purpose. The "sticking" of a relay may be caused by too much or unsuitably applied lubricant on the bearing parts of the magnet.

Unreliable switching-out of direct current apparatus is also particularly likely to arise with the connection shown in Fig. 156 (*a*), which is frequently used. In this case, the magnet coil has a permanent series resistance and the magnet armature is simply opened by the short-circuiting of the coil. In such a switching process, the current in the magnet coil does not fall immediately, but decreases as in the curve in Fig. 156 (*b*) asymptotically to zero. This dying away of the current makes the opening of the magnet less certain. A sudden interruption of the current is better since it immediately removes the magnetic pull.

In the case of a.c. no-volt coils with slow voltage drop, the release may fail, since the armature does not fall off quickly and completely, but oscillates in a half-open position.

Chapter XXVI, para. 1 (c), has already referred to the high over voltages arising on switching-out d.c. magnet coils. The coils of relays or protective devices will usually withstand these over-voltages. On the other hand, the trouble may occur in

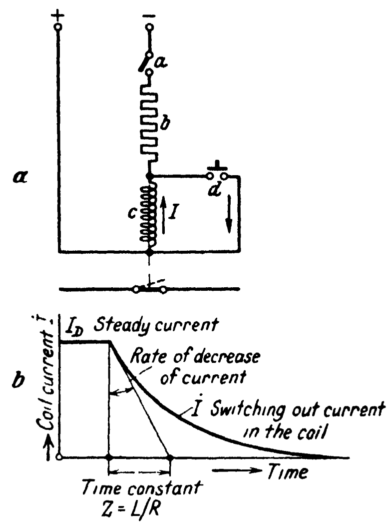


FIG. 156. D.C. SWITCH SOLENOID OR CONTACTOR

(a) Diagram of connections.
(b) Current flow in the short-circuited loop. c . . . d, when switching out.
a = Closing contact. c — Switch solenoid coil or contactor.
b = Buffer resistance. d — Switching-out contact.

the remaining parts of the plant, which are electrically connected with the circuit of the magnet coils, obviously at those places where the insulation is weakest.

(b) HUMMING OF MAGNETS. Humming is caused in magnets by the pulsating magnetic field. Short-circuited turns are placed on the opposing surfaces of the magnet to prevent the disappearance of the magnetic pull when the current is zero. They serve the purpose of inducing a magnetic field, displaced as regards time, in that part of the pole shoe which is enclosed by this winding. Defects on these short-circuited turns, for example, faulty soldered places, bad riveting, or wrongly dimensioned air-gaps may cause marked humming. In a.c.

magnets, a very important factor in reducing humming is the good fit of the opposed surfaces.

(c) SPARKING ON CONTACTS. Chapter XXV, paras. 2 and 3, give general information on contact troubles. A fault particularly characteristic of contacts must, however, be mentioned here; that is, sparking on switching-in. This phenomenon is generally traceable to faulty design, as a result of which the size of the masses to be accelerated, their switching-in speed, and the contact pressure are not properly adjusted to one another. By choosing a spring with the proper characteristic the fault can usually be cured. Mention has also been made (Chapter XXVI, para 1 (a)) of the appearance of sparks due to flash-overs on switching-in, when, particularly with high voltages, the arc flashes across the space between the contacts before they are closed.

CHAPTER XXX

PROTECTIVE RELAYS

For protecting generators, transformers, and transmission lines the following protective relays are generally employed nowadays—

Overload relays with inverse time lag.
Overload relays with constant time lag.
Reverse power relays.
Differential current relays.
Distance or impedance relays.

Reverse power or differential current relays are used for the internal protection of generators and transformers, while the other types mentioned are used for isolating a defective part of the supply The construction and application of all these relays are outside the scope of this book, but in recent literature authoritative publications on the subject can be found.

The construction and principle of application of many relays for the protection both of generators and transformers and of the supply is still a subject of discussion and controversy. Without attempting any general explanation, the information given here serves the purpose of making clear to the practical engineer the principles of the protective relays mentioned and of acquainting him with the troubles to which they are liable.

1. Overload Relays with Inverse Time Lag. Typical characteristic curves for these relays are shown in Fig. 157. The current/time curves show that the time of release rapidly becomes shorter after a certain current is exceeded. If the releasing current is 5 or more times the normal current, the time lag finally remains almost constant. This type of relay formerly afforded a sufficiently selective protection in many cases, but it cannot, of course, be compared with the modern selective relay. Since, however, installations were at one time operated electrically independently of one another, relays with a release dependent on the current gave the best selectivity, particularly in branched systems supplied from one

source. In such distribution systems, the relays on the switches nearest to the power station were fixed for a high tripping current. The relays on the further switches of the supply then had smaller and smaller tripping currents according to their distance from the station. To attain effective protection in this way, a precise knowledge of the short-circuit currents which may occur at the different places in the supply is necessary.

In spite of very simple conditions on the transmission system

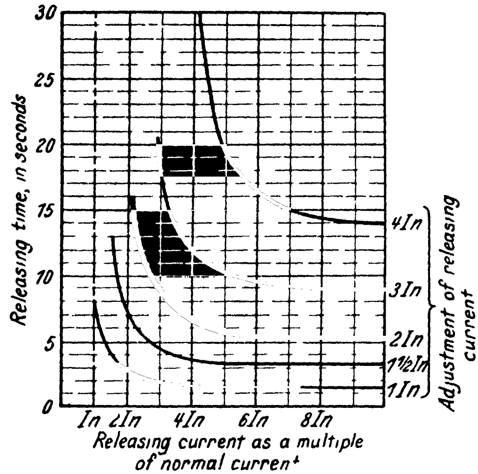


FIG. 157 OVERLOAD RELAY WITH INVERSE TIME LAG
Release times relative to releasing current with different positions of the magnet core

this type of protection often could not be employed to give exact selectivity, due to the fact that the tripping current value was not fixed according to the principle mentioned above but with regard only to the probable overloads

A disadvantage of these relays, which are generally constructed with eddy current discs, is the so-called *over-running* with unsuitable constructions. By this is meant the continued running of the rotating disc even after the short circuit has been cut out. With properly designed relays this trouble can be completely prevented, by magnetic dampers operating on the rotating disc. Relays with releasing devices which release instantaneously when a short circuit or heavy excess current occurs are quite unsuitable. This property is a

characteristic of most relays with thermally operated time lags or with damping by fluids. Such relays can only be of use to single consumers for simple overload protection.

Relays with inverse time lag are generally only constructed as secondary relays and are therefore not supplied directly but through a current transformer. For this reason they can be built comparatively easily to be proof against very high primary short-circuit currents. The mechanical effect of these current impulses is easily withstood when the eddy current rotating disc is equipped with a slipping drive.

Unlike the usual types of electromagnetic relays consisting of a magnetic circuit in which the iron armature is built as a movable member, relays with eddy current discs have the great advantage that they neither hum nor vibrate. The running times of these relays, as of all other relays employing the eddy current principle, are dependent on the frequency. Since their torque varies approximately as the square of the frequency, they may not trip with a comparatively small drop in frequency unless the current is higher.

2. Overload Relays with Constant Time-lag. As suggested by their name, these relays have a time of release which is adjustable and independent of the current. The tripping current is generally adjustable at will within a range with a ratio of the limiting value of $\frac{1}{1\cdot8}$. Different manufacturers make this relay in two different types for primary and secondary circuits.

In a primary relay the current coil is connected directly in the conductors carrying the main current. The beginning of the current coil is arranged, therefore, in metallic connection with the relay mechanism, while the end of the coil is insulated from the body of the relay, although only for the highest voltage occurring between the coil ends. The whole primary relay is so made that it can be fixed directly on to the oil-immersed switch terminals and therefore remains permanently under voltage. On this account adjustments cannot generally be made to it during service, or at least only by means of a bar specially insulated for the purpose. The opening of the switch by a primary relay is usually by direct mechanical tripping of the mechanism of the oil switch. Since this type of relay does not require a current transformer, it is very widely used to-day.

The second type of relay with constant time lag is not different in principle from the first, but its operating coil is connected on to the secondary winding of a current transformer. Since this is insulated from the supply voltage and earthed, the secondary relay represents a low voltage apparatus which, together with other equipment such as meters and regulators, can be fixed on the low voltage switchboard.

Both groups of relays generally have an adjustable device by means of which an instantaneous tripping at a multiple of the rated current can be obtained, while with smaller excess currents the fixed time of releasing is retained.

These relays with constant time lag are subject to the following general troubles—

1. On the occurrence of short circuits, they may not withstand the electrodynamic forces which arise. Primary relays are specially likely to be damaged in this way, since there is no limiting of the short-circuit current by a current transformer, as is the case with a secondary relay. The protective resistances which are intended to prevent the building up of transient waves with large short circuits, and are connected in parallel with the current coil, may not be in order due to having wrong resistance values or being insufficiently securely fixed, and consequently solder may be thrown off and cause flash-overs.

2. The relays may not be proof against short circuits, that is, the adjusted time lag is not maintained when heavy short circuits occur, and the relay trips. The cause of this trouble is to be found in the time delay mechanism of the relay.

3. The relay may continue to operate after the short circuit has already been cut out. The trouble is usually that the relay is structurally incomplete, in that the current has to return to a much lower value than the tripping value, before the armature of the relay can drop.

4. The relay, especially if a primary relay, may have insufficient releasing force, the work of freeing the oil switch latch mechanism being greater than that provided by the relay. For heavy-current oil-immersed switchgear, in order to prevent any uncertainty, it is customary to provide an indirect release.

Failures of the release on supply systems with relays having constant time lags may also occur under such circumstances as are shown in Fig. 158. When a short circuit occurs at *b*, the

voltage at the point *a* is greatly reduced, and on this account the synchronizing force which holds the two power stations in step is appreciably reduced. They may no longer run in synchronism but "hunt," so that the voltage at the point *a* constantly fluctuates between a certain maximum value and zero. The short-circuit current flowing towards *b* also varies

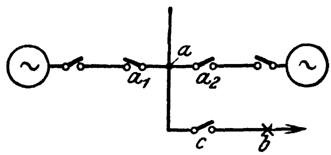


FIG. 158. ARRANGEMENT OF A SUPPLY WITH POSSIBLE LINE RELAY FAILURES

(*a*) Position of junction; a_1a_2 coupling switches.
(*b*) Position of short circuit. (*c*) Line relay.

in phase with this voltage variation. It may then easily happen that the relay for this part of the circuit falls back after each current surge, particularly if it has a high dropping out current, which from the point of view of other processes is desirable. In this case the faulty part of the system is not switched out at all, but any switch on the mains from the power station may be wrongly tripped instead.

The application of this type of relay for selective protection is necessarily limited, being practicable in systems supplied

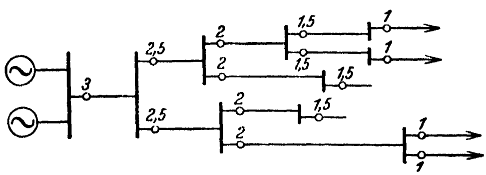


FIG. 159. DIAGRAM OF CONNECTIONS OF A SUPPLY DISTRIBUTION SYSTEM. STEPPING OF THE RELEASE TIMES OF THE CONSTANT TIME LAG OVERLOAD RELAYS

Constant release times in seconds.

from one source only, and even then only if the number of supply sections in series is not too great. The setting is then stepped as in Fig. 159, so that the switches near the station are given the longest time of release and those farther away have gradually decreasing intervals before they are released. It can easily be seen that this protection is only reliable in service if the stepping between adjacent relays is fixed so that

there is the smallest possible difference between the times at which they are released. In modern relays and oil-immersed switches, it is hardly possible to make the stepping intervals less than 0·5 sec. For this reason this protective system leads to long release times and consequent interruptions in operation when short circuits occur near the power station. A certain improvement of the selectivity can be achieved with this relay permanently in connection with other auxiliary apparatus, as shown in the following section.

3. Reverse Power Relays. Up to the present day these relays have been generally employed for selective protection against the internal breakdowns of generators. They operate according to the direction of the energy flow and are so connected that when it is reversed, that is, when the generator takes energy from the supply, they trip the generator switch. On that account, protection is not obtained in the case of single generators, but operates selectively when generators are working in parallel.

These relays are built and used in a great variety of connections, single and polyphase. Many of these connections and constructions have the disadvantage that they do not operate solely on the energy flowing, but are also dependent on the power factor, so that they may be released unnecessarily with any large inductive generator load. The latter fault may arise when switching in long overhead lines or cables.

The main requirement of a reverse-power relay is that it should operate satisfactorily with a pure wattful characteristic; that is to say, it must be completely independent of the power factor.

In order to ensure reliable operation of the protective devices for any possible internal generator defect, at least two relay systems must be provided for each generator. In Fig. 160 this type of protection is afforded by a two-pole reverse power relay. In each system a torque occurs due to the effect of the current of one phase on the appropriate voltage, which is phase displaced by 90°. By suitable auxiliary devices, this arrangement can be made to respond entirely to the wattful component of the current.

Certain operation under all circumstances for every possible internal winding defect cannot be provided by reverse power relays alone. The load which flows back to the defective generator depends entirely on the position of the fault. If

it is at the beginning of the winding near the terminals, the load flowing back to it is much greater than when the defect is in the interior, that is, near the star-point. In the latter case, the flow of energy may or may not be reversed.

The operation of the reverse power relay is also very uncertain when defects occur in the field-winding. Then, even with the excitation completely removed, the generator may feed at least to a certain extent into the supply as an asyn-

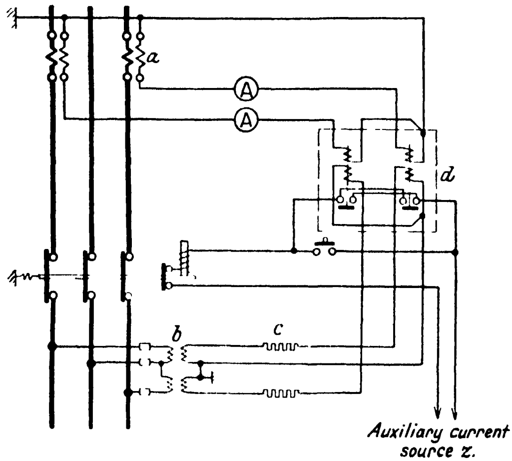


FIG. 160. DIAGRAM OF CONNECTIONS FOR A TWO-POLE REVERSE POWER RELAY

a = Current transformer. *c* = Buffer resistances.
b = Voltage transformer. *d* = Relays.

chronous generator. The flow of energy is then not reversed and nothing causes the relay to operate. The protection afforded by this type of relay may be valuable in another direction since it protects the group of machines against the occurrence of dangerous torque impulses. These may be due to switching processes, for example, faulty paralleling. Such occurrences are particularly dangerous mechanically, since they occur as shocks and often start "hunting" between the generator and the supply. The result of this may be to damage the couplings. In the effort to attain reliable operation in this respect, the relay may easily be made too sensitive so that it operates unnecessarily even if quite trifling load surges occur when paralleling. Many types of reverse-power relay

have also the disadvantage that with low voltages which may exist immediately on the occurrence of trouble, they no longer operate with any certainty.

Before the use of efficient distance relays, selective protection of the supply was sometimes attempted by means of reverse-power relays. This was generally in conjunction with overload relays having inverse time lags when the reverse-power relay had to act as a barrier relay. A simple example of the application of this kind of protection is shown in Fig. 161. A power station supplies a divided supply system over a double set of conductors. If in one of the supply lines a short circuit occurs, the short-circuit current not only flows directly out from the power station but also round the path formed by the sound supply line and the bus-bars back to the place of short circuit.

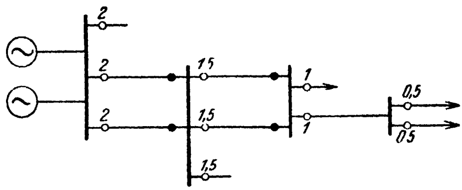


FIG. 161 DIAGRAM OF CONNECTIONS OF A SELECTIVE PROTECTIVE SYSTEM

○ Overload relays with inverse time lags
● Reverse power relays or directional relays

To ensure that only the defective supply line is switched out, the reverse power relay ought to hold in the sound supply line and only trip the switch belonging to the faulty supply line. The energy in the sound supply line will flow through to the bus-bar and back in the faulty line away from the bus-bar. The inadequacy of the protective system is immediately apparent. The faulty supply line is disconnected at once on the load side: at the power station side, on the other hand, only after an interval corresponding to the time interval of the relay fixed at this point.

4. Differential Current Relays. These relays are to-day generally used for the protection of generators, but until recently they were used solely for the protection of transformers.

The principle of operation is dependent on the balancing of currents and on this account is practically independent of the value, and also of the working voltage. These relays operate entirely selectively.

Faulty tripping of differential relays occurs chiefly in the case of transformers, where primary and secondary current are directly balanced against one another (see Chapter XIX). On this account, when installing the relay, attention should

be paid to the effects due to magnetizing current. To ensure efficient operation of the relay it is necessary to take into account the wattless current surge on switching in, and the increase in the magnetizing current should the working voltage increase some 10 per cent or 15 per cent. For these two reasons the sensitivity of the relay must be limited.

The internal connection of the transformer must also be

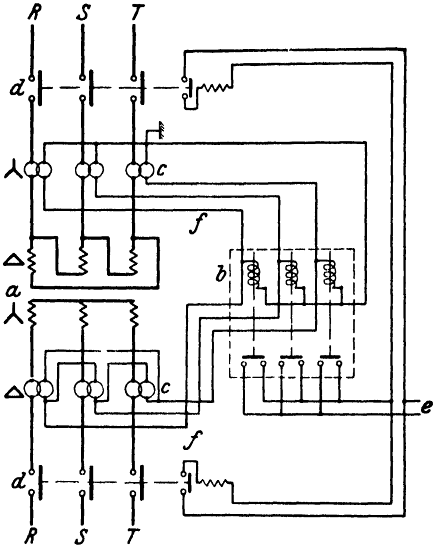


FIG. 162A. DIAGRAM OF CONNECTIONS OF A DIFFERENTIAL RELAY ON TO A $\curlywedge/\Delta$ TRANSFORMER WITH $\Delta/\curlywedge$ CONNECTION OF THE CURRENT TRANSFORMERS TO PREVENT OPERATION ON A BREAKDOWN TO EARTH

a = Three-phase transformer.	*d* = Oil switch with release coil.
b = Differential current relay.	*e* = Auxiliary current source.
c = Current transformer.	*f* = Circuit of the current transformers.

taken into account when installing a differential relay, since only with similar primary and secondary connections, that is, either star/star or delta/delta connections, are the currents in phase and suitable for direct application to the relay. With other types of connection use must be made of instrument transformers. With transformers connected dissimilarly (delta/star or star/delta) the current transformers must be suitably connected and in the reverse manner, that is, either star/delta or delta/star respectively. The diagram of connections in Fig. 162A shows the correct connection of the current transformers

according to the main transformer connection. If this rule for the connection is not adhered to and the current transformers, for example, are connected in star/delta when the main transformer is also star/delta connected, the differential current relay may operate wrongly as in the following case. The transformer is supplied on the star side (with earthed neutral point) and is open-circuited on the delta side. In one phase of

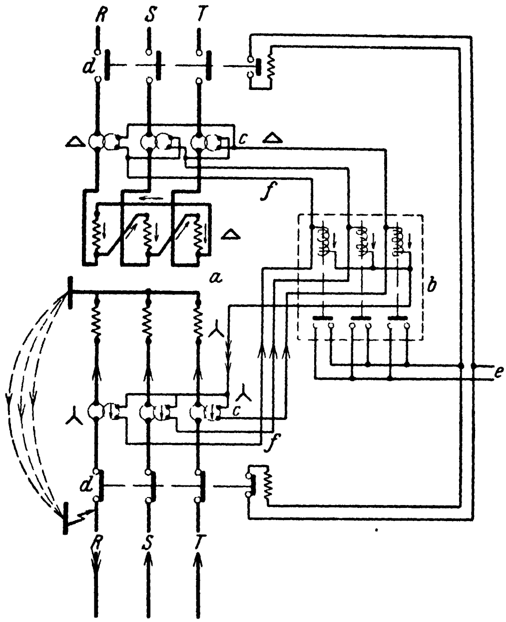


FIG. 162B. CURRENT PATHS IN THE TRANSFORMER WINDINGS AND RELAY CIRCUITS, WHEN THE CURRENT TRANSFORMER CONNECTION IS NOT SUITABLE AND A BREAKDOWN TO EARTH OCCURS

a	Three-phase transformer.	d	Oil switch.
b	Differential current relay.	e	– Auxiliary circuit.
c	Current transformer.	f	– Circuit of the current transformers.

the supply, outside the transformer, there is an earth and the earth current flows from this place to the star point of the transformer. With the current distribution now existing in the transformer, the current transformer circuits supply the relay only from the star side, while from the delta side the relay is without current. The reason for the faulty operation of the relay is, therefore, that the transformer is switched out without itself being the cause of the fault. Fig. 162B shows the current

paths in the transformer windings and in the relay circuits with this type of trouble.

Wrong tripping of the relay often occurs if the characteristics of the current transformers on either side of the relay are very different. These deviations are often unavoidable, if multi-turn current transformers with several primary coils are used on one side of the relay, and on the other side bus-bar current transformers with only one primary turn. An external

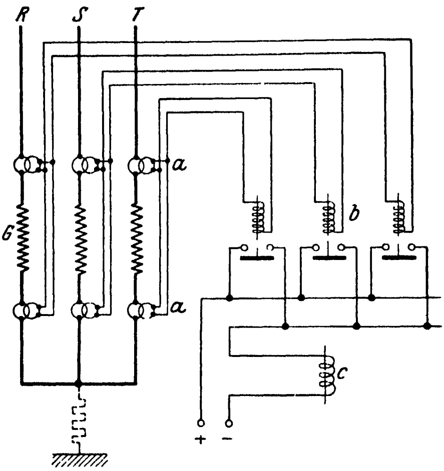


FIG. 163. DIAGRAM OF CONNECTIONS OF A MERZ-PRICE PROTECTIVE CONNECTION

G Generator windings. *b* - Differential current relay.
a Protective current transformer. *c* Main switch release.

short circuit can then quite easily trip the relay unnecessarily. This disadvantage can be cured in practice by the addition of a finely stepped intertransformer, or of adjustable impedances in the circuit of one current transformer. It is obvious that this protective system will not prevent internal trouble in a transformer but will only limit the effects of it.

Differential current relays cannot in all cases be relied upon for the protection of generators. With the usual connection of the Merz-Price type (Fig. 163), the relay does not operate at all on the occurrence of short circuits or breaks in conductors. On the other hand, the relay operates when the stator winding breaks down to the core, if it is properly adjusted for the conditions, this being chiefly dependent on the earthing of the neutral point. If the supply system fed directly from

the generator is large, and there is a breakdown to earth in the generator windings, without the neutral point being earthed, the differential relay is still effective since the capacitance current to earth is usually sufficiently large. If this is not likely to be the case, the neutral point should be earthed, usually through a resistance. The size of the earthing resistance in this case obviously has a great influence on the sensitivity of the differential relay. If it is comparatively large and there

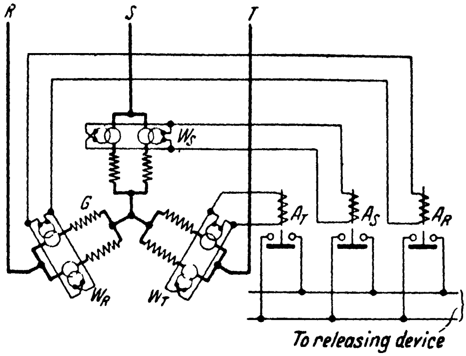


FIG. 164. DIFFERENTIAL RELAY ON GENERATOR WITH PARALLEL WINDINGS

G Generator. *W* Series transformers *A* Protective relay.

is a breakdown to earth, the fault current is limited to a smaller value, so that less damage is likely to occur. The protection, however, is less sensitive so that the relay will fail to operate when there is a breakdown to earth at a part of the winding adjacent to the neutral point.

Although the differential relay in this arrangement does not operate directly as a result of winding short circuits, it will nevertheless, in most cases, lead to their detection, since a winding short circuit as a rule means also a breakdown to earth. In bar windings with only one bar per slot, the occurrence of a pure winding short circuit is hardly possible, and can in any case only occur in the parts of the winding which lie outside the slots.

Numerous different types of protective devices operating on the occurrence of winding short circuits are available. Comparatively simple methods are quite sufficient for the protection of a generator having two parallel circuits. For the protection of such a winding six current transformers are necessary, supplying a 3-pole differential current relay as in Fig. 164.

Each pole is supplied from the two current transformers of the parallel-connected stator winding. If this connection, however, has added to it a further 3-pole differential current relay and the associated current transformers, the arrangement is an effective protection for all internal defects of a generator whether short circuits in the winding or breakdowns to earth.

In Fig. 165 is shown a protective arrangement against winding short circuits in generators with normal windings not

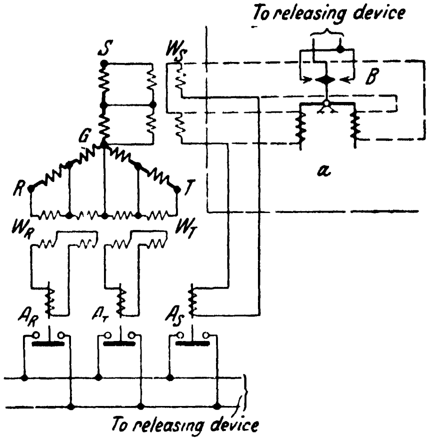


FIG. 165. DIAGRAM OF CONNECTIONS. GENERATOR WINDING PROTECTION WITH DIFFERENTIAL VOLTAGE RELAY USING MID-POINT WINDING TAPPINGS

a Connection with mechanical balancing relay for phase difference between the voltages being compared.

G = Generator.
$W_R W_S W_T$ – Potential transformer.
A Releasing relay.
B – Balancing relay.

having parallel circuits. In each winding phase, the middle point is tapped. and the two partial voltages are compared by means of a potential transformer. On the occurrence of winding short circuits or broken conductors—excepting breakdowns to earth—the two partial voltages are no longer equal in value and the differential relay operates. The arrangement is simple and completely selective.

It must be noted, however, that with these two latter connections for protection against winding short circuits, the two currents to be compared, and also the voltages, must be exactly in phase, otherwise the relay operates unnecessarily. If with the last scheme of protection, the two voltages are phase displaced, a balancing relay for each phase must be used,

with two magnetic systems which are entirely separate both mechanically and electrically as shown at *a* (Fig. 165).

5. Distance or Impedance Relays. The principal disadvantages of the relays in general use to-day for the protection of supply systems, described in the above sections, lead to the conclusion that an absolutely certain protection is impossible with such devices. The solution of the problem of supply system protection has advanced an important step forward in recent years as a result of the development of distance or impedance relays. An important problem is to satisfy the requirement that the relay time shall be as far as possible independent of the value of the short-circuit current and, in addition, that the relay shall operate reliably according to the direction of flow of the energy. The character of a short circuit occurring at any point in a supply system depends on the instantaneous effective generator outputs, and on the impedances of the generators and transformers. When the number of machines on load is greatly reduced, for example, during Sunday or in the night, a short circuit in the supply will not reach the usual current value for the system, necessary to operate the relay which was designed for it. The conditions are particularly bad in high-tension supplies which are only lightly loaded, as under these conditions the generators are weakly excited, so that the short-circuit current may only amount to between 10 per cent and 20 per cent of the rated current. It follows that the current values may not always give a clear indication of trouble which has occurred in the supply. A particular disadvantage of some systems is the extended time of release. The maximum time for tripping, having regard to the damage which may [illegible] done by the short-circuit arc, and in order to mai[illegible]nchronous operation of machines should never ex[illegible] should [illegible] A further difficulty is the diversity of the faults t[illegible] if the arr[illegible] which may be single pole or multi-pole short circuits [illegible] between phases or to earth. Alternatively there may be the joint effect of several faults due to the simultaneous occurrence of short circuits at different places in the supply. The development of distance relays was based on the conditions existing when a short circuit occurs. Not only the current but the impedance of the short-circuit loop—that is, the relation between the supply voltage and the short-circuit current—gives a correct indication of the distance of the short circuit. The use of the

impedance for fixing the distance of the faulty place is, however, not very certain since, according as the short circuit arises from direct metallic contact or from an arc, the voltage at the place of short circuit varies considerably. This condition is a further difficulty in the way of exact determination of the site of the fault and the consequent fixing of the switch tripping time. In a modern distance relay an ingenious connection is incorporated consisting of coils responding to the impedance, generally used as a tripping device in conjunction with additional coils operating on ohmic resistance. The impedance coils make possible the tripping of short-circuit currents far below the normal current, while the cable reactance operating through the ohmic coils fixes the relay time, which will be proportional to the distance of the faulty place.

6. Over-voltage Protection. Experience has shown that properly arranged and designed horn gaps with choke coils and resistances can protect electrical plant from many over-voltages. They are chiefly a protection against the over-voltages arising as the result of breakdowns to earth, which are the most common troubles met with in service. In addition, the horn gap is effective against high frequency transients and surges, when their voltages reach the flash-over voltage of the horns.

The protective resistances may be constructed as either water or metallic resistances. The correct proportioning of the resistance is most important if it is to be an effective protection. As a rule, the smaller the resistance is, the greater is the protection afforded by the apparatus up to a fixed limit. The smallest permissible resistance is dependent on the arc current, which should not exceed a certain value if it is to be extinguished with certaithe Jietween the horns. The arc existing on the horn after an cansformer.ᵓ is maintained by the working voltage until it is finn conducguished by electrodynamic and thermal effects in thevolt path. The length of the horns and the space for the spreading of the arc fixes the current strength which must be limited by the resistance. The performance of the blowout requires that the minimum current value be maintained just as the maximum value should not be exceeded.

It can be deduced from this consideration that water resistances are not particularly suitable for horn gaps, since their resistance is very dependent on the temperature. The minimum resistance must not be allowed to drop even with the highest

temperature arising in service. It should also be noted that the contents of a water resistance may decrease with time, and a decrease in water content of more than about 30 per cent is not permissible. If the water level is too low, the electrode is no longer sufficiently immersed.

For water resistances distilled water is most suitable, especially for voltages over 12 kV., since well water has too low a specific resistance. When putting in resistance values the figures on the rating plate should be checked and the actual temperature allowed for by a conversion factor. If the observed value of the resistance is too great, it can be reduced by the addition of soda, while when it is too small distilled water may be substituted for a portion of the existing water. In exceptional cases, the resistance may be raised to the proper value by the addition of small quantities of clean gravel. For measuring the resistance an a.c. resistance box is most suitable, in order to avoid the electrolytic processes which would occur in the water if direct current were used. If no resistance box is available, a voltmeter with a known high characteristic resistance R_v is sufficient. In the first place, the available a.c. voltage, V, from about 100–500 volts. is measured with the voltmeter. The water resistance is then connected in series with the voltmeter and the new voltage V_1 read. The resistance R_x is then calculated from the formula

$$R_x = R_v [(V/V_1) - 1].$$

Metallic resistances are more suitable for use as protective resistances, since they can be made independent of the temperature. They are generally oil immersed, and the danger of fire should be kept in mind. For this reason they are not suitable for power stations with no maintenance staff. It is also most important that absolutely dry oil should be used.

Horn gaps may work badly if the arrangement of the horns and resistances and of the choke coils is unsuitable. The horn should be connected between the supply line to be protected and earth. The connection of the supply line through the horn to earth should be as far as possible a straight line, particularly in cases where protection is required against surges or high-frequency transients. If the horn is not properly shaped, the arc may be conducted downwards and cracks and corrosion appear on its surface due to the steady arc.

With metallic resistances, a few resistance groups may be

short-circuited. Water resistances may have too low a resistance or too little water which quickly heats up. Too low a water level will cause the water to spray out when the horns are in operation. If the distance of the horns from the walls and covers is too small, the arc may jump direct to earth or to other parts of the plant. If the striking distance is wrong, it will obviously cause the gaps to operate unnecessarily. In indoor situations, the horns should be adjusted to about 1·4 times, and in the open air 1·8 times, the highest possible working voltage. The flash-over voltage depends on the thickness and shape of the horns.

Complete over-voltage protection can never be obtained with horn gaps alone, and in some circumstances they are not even a protection against over-voltages arising from breakdowns to earth. The use of other methods of over-voltage protection—for example, earthing of the neutral point or adding extinguishing coils—is in most cases effective. Finally, it should be noted that horn gaps only provide an outlet for an over-voltage which already exists, while the latter forms of protection can prevent the occurrence of the over-voltage.

CHAPTER XXXI

GENERAL CAUSES OF TROUBLE IN INSTALLATIONS

1. Wrong Cable Lay-out. Incorrect readings on measuring instruments, as well as relays which trip at current values differing from those originally intended, are a consequence mainly of badly arranged cables, particularly heavy current cables. Such conductors, on account of their heavy current, have a strong magnetic field which has its greatest density in the immediate vicinity of the conductor and has a field like

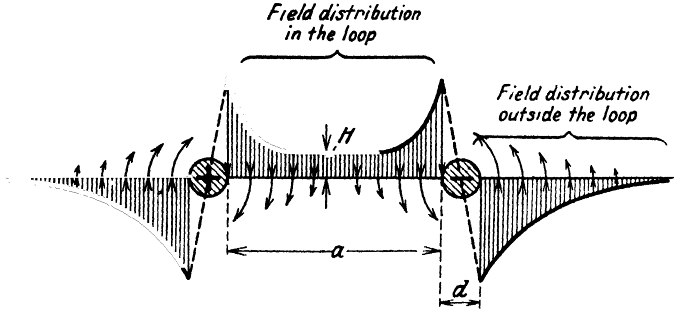


FIG. 166. HEAVY CURRENT "OUT" AND "RETURN" CABLES WITH THEIR SURROUNDING MAGNETIC FIELD

that shown in Fig. 166. It is apparent from this diagram that the field H in the plane through the two conductors increases in strength and in symmetry inversely as the distance between the conductors. If measuring instruments are mounted in the space between the conductors—for example, on switchboards—faulty recording by these is inevitable, particularly with the electromagnetic and electrodynamic types, as explained in Chapter XXVII, para. 1.

In addition, relays operating in conjunction with switches may be so influenced by heavy current conductors placed too near to them that the original tripping current no longer applies.

2. Unequal Current Distribution in Parallel Conductors. If a direct current circuit consists of several parallel conductors for the purpose of dividing the cross-section, there are frequently

unequal currents in the individual parallel conductors. The symmetrical distribution of the current becomes more difficult as the number of conductors increases. The ohmic resistance of each of these conductors determines its current loading. If the cables are comparatively short, as is generally the case, the contact resistances at the cable joints are, as a rule, greater than the resistances of the individual cables. According to the way they are mounted and bedded in, these contact resistances may themselves be very unequal and cause the current to be unequally distributed.

The contact resistances of bus-bars can only be slightly improved by tinning. Very slight greasing with vaseline is to be recommended as a protection for the contacts. Contact pressure has also a marked influence on the contact loss. The pressure also varies very much according to the bolt tension in the ordinary bolted contacts which are almost invariably used. At a good contact place, pressures of about 2 lb. per A. for single contacts and of 1 lb. per A. for double contacts are suitable. The pressures (in pounds) obtainable with steel bolts amount to about 7 000 times the bolt cross-section in square inches.

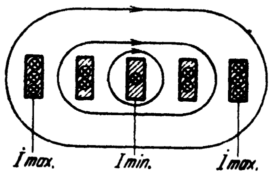


FIG. 167. FIELD AND CURRENT DISTRIBUTION WITH FIVE PARALLEL A.C. CONDUCTORS OF THE SAME PHASE

With alternating current conductors, the symmetrical distribution of current to a number of parallel conductors is even more difficult to achieve, since here there is the reactance in addition to the ohmic resistance to affect the current distribution. A clear picture of the reactance of parallel a.c. conductors is given by the magnitude or number of magnetic field lines linking the conductors in question.

If, for example, the alternating current phase shown in Fig. 167 consisting of five parallel conductors is examined, it can be easily seen that the conductor lying in the centre is surrounded by the greatest number of flux lines. Its reactance is therefore greatest. Similarly, the current loading in the interior of a thick solid conductor is smaller than at the surface of the conductor due to the so called *skin-effect*.

If each phase of a three-phase heavy current circuit is divided into several parallel conductors, the whole circuit should be so laid out that a part of each phase lies in an

individual cable and the three-phase conductors are grouped together as in Fig. 168. The impedance of such a group and of the whole supply is appreciably reduced by this, since the sum of the currents of a three-phase system is always zero, for which reason no magnetic field can build up round a group so formed. If a single-phase supply is in question the supply and return leads should not be arranged in one plane but in two parallel planes as shown in Fig. 169. Symmetrical distribution of alternating currents in parallel conductors may be achieved according to the means available by altering the lengths of bus-bars or cables, or else by encasing the cable in iron or similar conduit, which serves the purpose of altering the reactance of the conductor and therefore the current distribution.

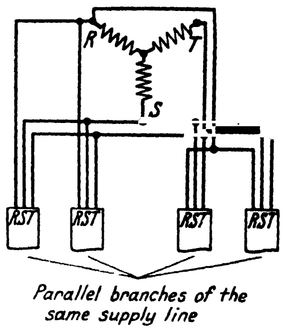


Fig. 168. Grouping of the Parallel Conductors of a Heavy Current Three-phase Supply to Avoid Unequal Current Distribution

3. Insulating Materials in Terminal Bushings. The exuding of sealing material from terminal bushings chiefly occurs on supplies with heavy currents. Its immediate cause is usually excessive heating of the bushing, or alternatively overfilling with compound in the first place. The heating may be indi-

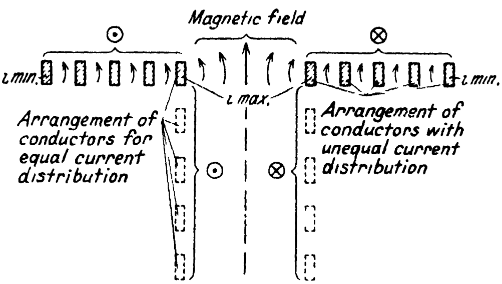


Fig. 169. Arrangement of Parallel Conductor Bars of a Single-phase Supply to Give Equal Current Distribution

rectly due to a nearby contact in the same circuit which has become loose. In bad cases the greatest care is necessary, as the bushings may explode. If deterioration has occurred on parts of bushings immersed under oil, certain compounds have

a tendency to absorb oil so that excessive swelling occurs which may crack the bushing. Compounds may also have hollow spaces caused by expansion and contraction in which corona effects arise, and heat the places concerned to an even greater degree. The latter has much the same effect as any other type of overheating.

With outdoor oil-immersed switches having oil-filled terminal bushings, a marked cloudiness of the oil may often be observed in the oil level gauge. Chemical analysis of the oil will then show various forms of sludgy products of decomposition, even when the bushing has been filled with perfectly clean and suitable oil. The phenomenon is due to a photochemical oxidizing process, in which the effects of light and air are combined. The clearer the oil in the first place, the more marked is the clouding or sludge formation. The dielectric strength of the oil is, however, not appreciably altered. The effect can be prevented by a completely air-tight sealing of the glass container and by placing a light proof cap over it.

4. Corona Phenomena. Corona phenomena on live constructional parts are caused either by the conditions mentioned above or by too sharp edges, wrong or defective earth connections, too low an oil level, or other defects. Isolating switch blades in the open position which remain under voltage on both sides from different supplies are subject to slight periodical glowing in conjunction with noise. If the two supplies are not running synchronously with one another, the voltage on the switch blade concerned varies continuously between zero and a maximum value when the two voltages are in phase opposition.

5. Wrong Tripping of Relays and Earth Leakage Indicators. Unnecessary tripping of relays, especially reverse power relays, may occur as a result of capacitance effects. This trouble is particularly likely when isolating switches are arranged pole by pole so that the voltage coils of the relays lying in each phase of the series are cross-connected, and the capacitances of the connected parts of the plant receive a charging current. A relay not having a pure wattful characteristic may operate wrongly for this reason. In high-tension plant with a directly earthed neutral point, currents flowing to earth are often indicated, although no actual breakdown to earth has occurred. An ammeter for recording earths may indicate, for example, when a certain switch is closed, for the

following reason. The three poles of a three-phase oil-immersed switch as shown in Fig. 170 do not close their buffer contacts exactly simultaneously. On this account, during the time in which the contact of one phase only is closed the magnetizing current of one phase flows through the ammeter which indicates a breakdown to earth. The duration of this current is naturally very short, generally only a few half waves. It can

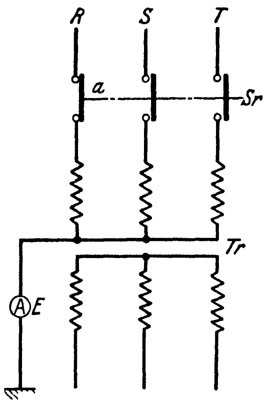


FIG. 170. WRONG INDICATION OF AN EARTH RECORDING AMMETER

a = First switch contact to close. Tr Transformer.
E = Earth indicating ammeter Sr Switch

be reduced to a minimum by more precise adjustment of the three contacts, and by switching in with the smallest possible delay. In the case of three-phase oil-immersed switches of the three-tank type, which consist of three quite separate switches, it is therefore an advantage to use adjustable couplings. Simultaneous closing of the three contacts is, however, even then not always possible. If in spite of more accurate adjustment of the contacts and couplings, the meter still registers unnecessarily, it is too sensitive and should be made less so by increasing the damping. Breakdowns to earth arising in service will still continue to be registered, since as a rule they are comparatively of much longer duration.

CHAPTER XXXII

STARTING EQUIPMENT

GENERAL defects exhibited by starting resistances, both of the air and oil-immersed types, and also by water resistances, are covered in Chapter XXVIII.

Troubles particularly experienced in connection with the starting of direct current and asynchronous motors are discussed in Chapter XII, paras. 2 and 3.

As regards starting apparatus in general, the principal remaining troubles are those associated with synchronous motors of which the following are the most important.

1. Starting Devices for Synchronous Motors. (*a*) ASYNCHRONOUS TAP-STARTING. This method of starting is chiefly used to-day on account of its simplicity and is similar to the starting of asynchronous squirrel cage motors. By means of a starting transformer with a tapping switch a reduced voltage is first applied to the motor. After the resulting start, according to whether the motor is started with or without load, it is put on to full voltage either directly or with an intermediate step. Various troubles may occur during this process such as flashovers on the slip-rings or on the rotor windings. These may be caused by the high voltage induced by the stator in the rotor at standstill. For this reason at starting the rotor winding should not be open-circuited, but should be short-circuited through a protective resistance. It is obvious that with any over-voltage phenomena the value of the existing resistance should be checked.

A wrongly proportioned resistance, for example, with a very high ohmic value, probably has no protective effect against over-voltages. On the other hand, if the protective resistance is too small, the energy absorbed in the field circuit is too great and the starting is poor.

If the starting voltage or the supply voltage itself is too low, the motor may refuse to start when cold after a lengthy period of standstill. For synchronous motors with salient poles without a damper winding, when determining the starting voltage the reduction in torque at half speed should be taken into account to ensure that the motor does not "lock in" at this

speed.* The starting voltage, and also the starting current, should not be set too low, but at the same time only chosen sufficiently high to be suitable for the motor and the driven machine.

When starting synchronous motors as shown in Fig. 171, serious trouble may be caused by a defective starting switch. Switching over from the lower to the higher voltage should take place either without interruption, or at any rate with very brief interruption, in order to prevent a drop in speed in the

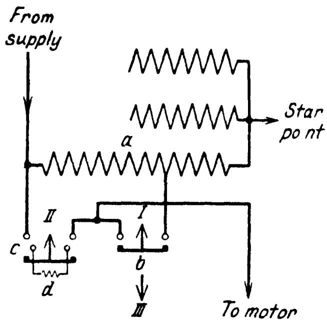


FIG. 171 FAILURE OF A TAP STARTING SWITCH

a — Starting transformer
b — Starting switch
c — Running switch
d — Protective resistance or protective choke coil
I–III — Successive switch movements

interval. In this case the coils lying between the tappings of the transformer are first short-circuited through a resistance. Before this resistance is bridged by the main contact, the connection with the transformer tapping must be opened and the arc arising must be already extinguished, or else a short circuit may occur in the winding step between the two tappings. If an autotransformer is used for starting, this defect often results in a complete breakdown since, as is well known, autotransformers are subject to very high short-circuit currents. Modern starting switches generally have suitably constructed interlocks to prevent such troubles.

(*b*) STARTING BY AN ASYNCHRONOUS MOTOR. With this method of starting the asynchronous starting motor has a lower number of poles and therefore a higher synchronous speed than the main motor. By means of a finely stepped adjustable starter, generally a liquid starter, the slip of the starting motor

* See *Journal of American I.E.E.*, 1920, p. 34, A. Hay.

is so regulated that the main motor can be connected in parallel with the supply as for a synchronous generator.

In this connection, it should be mentioned that the speed of an asynchronous motor can only be adjusted to a sufficient extent by the rotor resistance when the motor has a certain amount of load. The rated output of the starting motor should on this account be suitable for the no-load losses, including the exciter losses of the main motor; that is to say, it should be sufficiently loaded with these.

(c) STARTING WITH A SYNCHRONOUS INDUCTION MOTOR. In this case, the starting motor has the same number of poles as the main motor and after starting asynchronously is synchronized prior to synchronizing the main motor. The coupling of the starting motor and the main motor should be such as to ensure that the rotating field of the latter has its correct position when the former is synchronized, so that paralleling with the supply is then possible. It is a serious defect when the synchronized starting motor goes into synchronism with reversed polarity. The rotating field of the main motor is then displaced a pole pitch relative to the stator field. If there is no electrical interlock on the switch, this possibility should be kept in mind.

CHAPTER XXXIII

FIELD REGULATORS

1. Generator Voltage Regulation with Rheostats. The types of automatic voltage regulators usual to-day can be divided as regards their principle of operation into rheostats and vibrating regulators.

The first type of regulator imitates the manual process in that by means of a suitable automatic drive a resistance is so varied that the quantity to be controlled, for example, voltage, current, load, power factor, etc., remains constant.

(*a*) REGULATING PROCEDURE. The variation of the magnetic field of a generator, and therefore the resultant voltage adjustment do not take place simultaneously with the movement of the rheostat, but with various time delays according to the design, size and speed of the generator. After an alteration in the working conditions and the associated voltage alteration the regulator should bring the voltage as rapidly as possible to the required value. On this account, it should alter the rheostat in the first instance to something beyond the new equilibrium value. The adjustment of the excitation from one operating condition to another is thus done by over- or under-excitation, the degree of over-excitation being adjusted automatically. The larger the so-called *magnetic time constant* of the machine is—that is to say, the more the field variation lags behind the resistance variation—so much larger must be the over-excitation on the field regulator. In order that the voltage value being adjusted should not deviate appreciably from the steady value at which it is to be maintained, the over-excitation must be reduced before there is an actual excessive alteration in voltage. If this takes place too late, and the field regulator remains too long in the over-regulated position, or if it moves backward too slowly into the new position of equilibrium, an excessive change results. This means that the regulator must again operate in the opposite direction to correct the excessive over-regulation, and the same trouble may recur. The change to the new permanent position in this case takes place with many oscillations to and fro and, with very unfavourable conditions, may result in permanent hunting. Its cure is

generally possible by proper adjustment of the damping and the recoil.

Accurate rapid regulation of an electrical quantity can only be ensured by proper interaction of the two regulator parts. It is usually achieved in the following ways. (See Fig. 172.) The generator has a certain load and a suitable exciter voltage to maintain the terminal voltage constant. Thus the contact position of the rheostat remains steady at the point 1. In this operating condition the main spring *f* just balances the pull

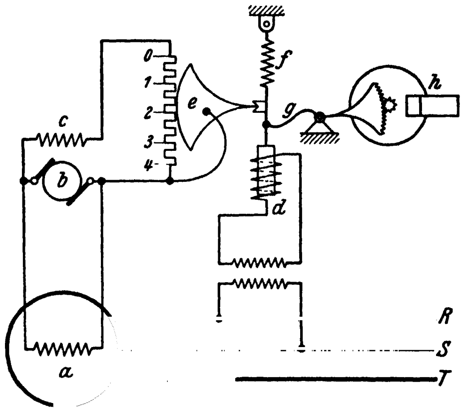


FIG. 172. DIAGRAM OF CONNECTIONS AND ARRANGEMENT OF A RESISTANCE REGULATOR

a = Alternator with field winding.
b = Exciter.
c = Field winding of the exciter.
d = Voltage magnet or operating mechanism.
e – Contact apparatus.
f Main or adjusting spring.
g Recoil spring.
h – Damping.

of the voltage magnet. This state of equilibrium, however, alters immediately if the electrical loading, the speed, or any other of the quantities alters. If, for example, the load decreases and results in a rise of terminal voltage, a corresponding movement of the magnet takes place, tending to produce a voltage drop. It will come to rest, for example, in position 3 due to the increasing tension of the recoil spring *g*. The damper disc was originally at rest, but begins to move under the pressure of the spring *g*. By appropriate adjustment of the contacts, the regulating resistance is so far raised that the exciter voltage is reduced by an appreciable amount. The exciter current, however, cannot follow the exciter voltage immediately, on account of the self-induction of the rotating field winding. As

soon, however, as the reduction of the exciter current becomes appreciable due to the decreased voltage on the regulator, the tractive force of the magnet decreases and reduces the tension of the spring *g*. The magnet *d* moves farther backwards, so that the contact apparatus ultimately arrives at position 2, and as a result a higher exciter voltage arises. In the meantime, the damping disc has rotated so far that the spring *g* no longer has any tension on it. If at this moment the generator voltage has again reached its normal value, the regulating process is complete.

The characteristic of this process thus consists in altering the exciter voltage past the value which corresponds to the new load condition. Without this over-excitation, rapid regulation is not possible. The corresponding regulating curves are shown in Fig. 173 compared with a regulating process without over-excitation.

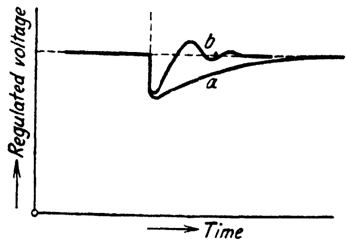


FIG. 173. REGULATING PROCESSES

a Voltage regulation curve without over-excitation.
b Voltage regulation curve with over-excitation

(*b*) HUNTING. Previous mention has been made of the importance of the over-regulation being stopped at the correct time if the regulating process is to be free from hunting. If, for example, the running time of the damper disc is short, the tension on the restraining spring *g* is released too soon. The movement of the magnet and consequently the over-regulation is then too great. On this account a marked voltage variation arises which forces the regulator to the farthest point. The running time for the damping apparatus is directly dependent on the magnetic time-constant of the machine, that is, on the rapidity with which the terminal voltage varies after a certain exciter voltage change.

The causes of hunting are so numerous that they cannot be exhaustively discussed here. Only a few of the most important characteristic types of hunting will be mentioned.

1. The damper disc in Fig. 172 remains almost stationary, the magnet system then moves to and fro with the contact apparatus, and the hunting is very rapid.

2. The damper device moves almost in phase with the contact apparatus. The damping appears to be rigidly coupled

with the magnet system and the contact apparatus. In this case, the hunting is very slow.

In the first case, the trouble is usually over-regulation, that is to say, very high regulating speed with too retarded a recoil to correct the over-regulation. Since the damping device is already at a standstill, it is useless to increase its force. A more effective expedient is to increase the strength of the recoil spring, that is, to make its characteristic steeper. The second type of hunting is caused by the opposite conditions. The recoil spring is too strong, the over-regulation consequently insufficient, and combined with this there is too low a regulating speed and too early recoil of the over-regulation. This can be cured by increasing the damping or weakening the recoil spring to give the required regulating speed.

Other causes of hunting in regulators are—

1. Too great friction and consequent lack of sensitivity. This trouble can be easily detected.

2. Too great or unequal stepping of the field regulator. In this case the regulator hunts with a high speed of oscillation, since even with small movements of the magnet system it over-regulates.

3. Too small field regulator resistance so that over-regulation is impossible. The regulator in this case hunts slowly and goes from a position at one end of its range to the other end.

4. Regulation in the unstable range of the magnetizing curve of the exciter. In this case, with a rapid regulator, the generator voltage can nevertheless be maintained practically constant by suitable adjustment of the recoil and damping. The regulated voltage will, however, always fluctuate slightly although within permissible limits. With adequately proportioned exciters this condition can be improved by incorporating a resistance directly in the circuit of the rotating field. The exciter is forced by this to work with a higher voltage and thus in a stable range. This expedient, however, results in greater losses in the exciter circuit.

5. Too much axial play of the regulated machine causing the magnetic flux to pulsate continuously and the regulator continually to swing with it. Also irregularities on commutators, field coils and other parts as described in Part 1.

6. Unstable operation of the governor of the driving machine so that the speed (and with parallel operation the loading also) alters periodically. In bad cases, the turbine governor and the

voltage regulator may have a joint effect resulting in resonant fluctuation. This can generally be easily cured by altering the characteristic of one regulator so that the disturbing frequency is displaced out of the critical range If both turbine governor and voltage regulator are to work properly together they should each operate alone in a stable manner

7. Abnormally strong residual magnetism of the exciter, making rapid regulation impossible. This should be cured by modifying the exciter.

8. Wrong brush position of the exciter: i.e. greatly displaced brushes, in conjunction with a large voltage drop in the exciter so that the influence of the regulator is too small. When the brushes are displaced too much, this gives the exciter a compounding characteristic and consequently increases the regulating time. The speed of adjustment of the exciter voltage, due to the influence of the compounding, is in this condition considerably dependent on the main current, the rise of which takes place too slowly.

9. Too great a voltage drop in the generator itself. This becomes apparent when, on sudden load surges, large voltage variations occur.

Even in the case of generators with normal voltage drop. and more often with excessive voltage drop, a voltage variation is naturally unavoidable with load surges. All regulators operate immediately after an alteration in the quantity to be regulated. On the other hand, the deviation of the regulated quantity from its normal value, as regards the duration and extent, is only dependent on the speed and sensitivity of the regulator. The highest possible sensitivity of the adjustment is always to be desired, particularly when the regulator has the task of reducing as far as possible the effects of sudden load peaks. The sensitivity varies in rapidity with the adjustment. On the other hand, increase of sensitivity is limited, in that the regulator continuously makes small rapid oscillations if it is actuated by the smallest periodic variations of the load or of a belt or gear drive. With this type of trouble, the regulating apparatus is only wearing itself out without any practical advantage being gained.

With automatic voltage regulation of d.c. generators there is the consideration that this simultaneously means regulation to constant output. The hunting of a d.c. regulator causes the governor of the driving machine to move, which may easily

lead to opposed hunting of the two regulators. This can easily be cured by an adjustment of the two regulators to very different speeds.

(*c*) CARBON PILE REGULATORS. Metals are generally used as resistance materials for rheostats, and do not need any special comment. Water resistances are very rarely used. Recently *carbon pile regulators* have been used which are constructed of disc shaped carbon pieces arranged in a pile. The resistance variation is obtained by variable axial pressure on the pile by which the contact resistance between the single discs can be altered considerably. Carbon pile regulators have the advantage that the resistance is not altered in steps, but smoothly between the maximum and minimum values. The carbon pile has the disadvantage, however, that its resistance is dependent on the temperature. Since the regulating of the carbon pile, that is, the difference of the pile lengths for the limiting values of the resistance, is very small, the temperature influence is very marked. In the usual types of carbon pressure regulator, it is necessary on this account for the carbon piles to be adjusted from time to time so that the apparatus may fulfil its purpose. In addition, the electrical loading capacity of the carbon pile is very limited. When a certain temperature is exceeded the pile disintegrates into dust and becomes useless. Even within the permissible loading limits a marked loss of carbon dust can be noticed on the discs, caused by the ordinary regulator movements. The unfavourable shape of its characteristic makes it necessary for it to be controlled by complicated poles or curved discs, making it difficult to attain precise regulation.

(*d*) INDIRECT REGULATORS. Similar comments obviously apply to indirect regulators of which the contact apparatus is not directly coupled to the rotating drum but operates through an oil servomotor. These regulators also operate on a principle of over-excitation, and hunting, according to the cause, can be cured in the same way by suitable adjustment of the recoil spring or the damping. Indirect regulators are also mostly equipped with fluid damping, generally oil dampers. The effectiveness of the damping depends on the viscosity of the oil, which may vary considerably, according to the temperature.

2. Generator Voltage Regulation with Vibration Regulators. The principle upon which the vibration regulator works is as

follows. A buffer resistance in the exciter circuit is periodically short-circuited by vibrating contacts, and the total resistance value thereby lowered. The extent of the variation of the resistance is fixed by the frequency and duration of the short-circuits, and is directly controlled by the value to be regulated. The losses which arise in the resistance units of resistance regulators, and which are removed by radiation and convection, must in vibration regulators be partly taken up by the vibrating contacts. Their life and their load capacity are therefore limited. When the contacts are overloaded, there is the danger that they will become welded together. In service, a regular reversal

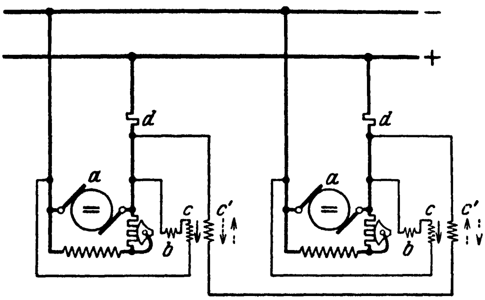


FIG. 174. STABILIZING CONNECTION FOR THE VOLTAGE REGULATORS OF TWO PARALLEL D.C. GENERATORS

a D.C. generators
b Voltage regulators
c Field windings of the regulators
c′ Stabilizing windings of the regulators.
d Stabilizing resistances

of the contact polarity is necessary to reduce the contact wear, and recently this switching over has been done automatically. The advantage that vibration regulators have over rheostatic regulators is their somewhat higher regulating speed. In the case of large generators, however, this difference does not arise, as the time constant of the main alternator field is appreciably greater than that of the exciter. The factor governing the speed of regulation, particularly of the voltage rise, is primarily the load capacity of the exciter.

3. Regulation with Parallel Operation. (*a*) D.C. GENERATORS. (See also Chapter IX.) When several d.c. generators are operating in parallel and each generator has a field regulator of the so-called *automatic* type, regulating to a constant voltage, unavoidable voltage and load variations occur even when the individual generators exhibit sufficient internal voltage drop. For stable parallel operation with automatic regulators, there

must be a stabilizing device supplied from the current through each regulator, which immediately balances any unequal current distribution. (See Fig. 174.) On the other hand, satisfactory parallel operation is possible without auxiliary devices with hand-operated regulators. There is, however, the disadvantage that the regulated voltage does not remain constant from no load to full load, but fluctuates.

(*b*) ALTERNATORS. (See Chapter X, paras. 2–5.) The voltage regulation on alternators running in parallel, unlike that of

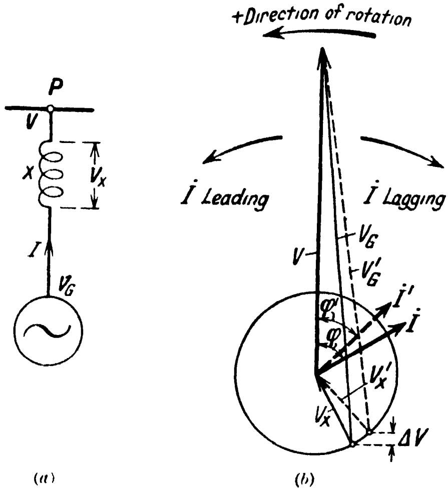


FIG. 175. EFFECT ON THE VOLTAGE REGULATION OF INDUCTIVE REACTANCES BETWEEN GENERATOR AND SUPPLY
(*a*) Diagram of connections (*b*) Vector diagram.

d.c. generators, is practically free from trouble. Alteration of the generator excitation with parallel operation only affects the wattless load distribution. The working load of the generator is fixed only by the governor position and the torque of the driving machine. Voltage regulators on alternators in parallel serve the purpose of distributing correctly the wattless load. Regulator hunting therefore only results in hunting of the wattless current, without influencing the governor of the driving machine.

The control of the wattless current distribution by automatic voltage regulators becomes easier as the reactance between the generators increases, as shown in Fig. 175 (*a*)

and (*b*). It is assumed that a generator operates on a supply system through a reactance X. V is the vector indicating the magnitude and direction of the supply voltage, I the load current and ϕ the phase angle. The generator is over-excited, and its power factor inductive, that is to say, there is a magnetizing wattless current fed into the supply. The voltage V_x across the reactance is phase displaced 90° in front of the load current I. The necessary terminal voltage on the generator must on this account be higher than the supply voltage at the point P, and is represented by the vector V_G. If now for any reason the wattless current increases, the phase-angle between generator current and line voltage increases further and the power factor is smaller. At the same time, the voltage vector alters its position due to the reactance, so that the generator voltage must rise about ΔV. This voltage change and the associated increase in wattless current opposes the voltage regulator, which accordingly maintains the voltage constant.

The diagram shows that with an alteration in wattless current the greater the effective reactance between the generator and the supply the more the generator voltage must rise. For this reason the wattless load distribution between generators and power stations, which must run in parallel through transformers or long overhead supply lines, can be very easily carried out by automatic voltage regulators, which also reduce the danger of overloading with wattless current

In this respect the conditions for the generators of a power station are much more unfavourable when they are directly connected through bus-bars, so that there are no reactances to have a stabilizing effect. When using ordinary automatic voltage regulators single generators tend to develop wattless current, in other words, run over-excited, while other generators tend to absorb wattless current and so run under-excited. Good parallel operation is, however, possible even in this case by using suitable wattless current stabilizing devices which ensure the automatic distribution of the wattless current to the generators. The voltage regulators should at the same time be made sensitive to the power factor, so that when the power factor is low the voltage is suitably regulated. The generator voltage thus follows the requirements of the supply, so that an excessive wattless circulating current cannot arise.

4. Synchronizing. (*a*) POWER SURGE. Entirely reliable remote control of the oil switch is the first requirement for successful synchronizing. The shorter the total closing time, that is, the time between the first switch movement and the actual closing of the buffer contacts and also the main contacts, the easier is it for the engineer or the automatic control to synchronize without surge. Theoretically, paralleling entirely without a surge requires absolute matching of both frequencies and also the exact coincidence of both voltage vectors, zero phase displacement and equal voltage values. This condition is, however, neither necessary nor attainable in practice.

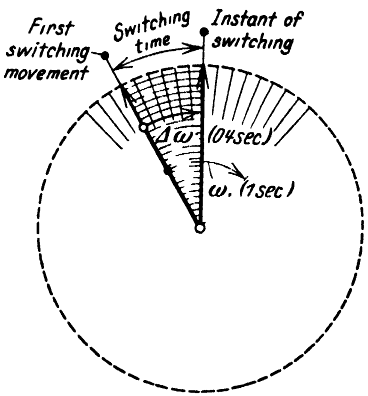


FIG. 176. POSITION OF SYNCHROSCOPE POINTER FOR PARALLEL SWITCHING

For practical purposes the operator can judge the frequency deviation when synchronizing from the speed of the synchroscope, or the phase voltmeter. The limiting value for the difference in frequencies amounts to about 0·2 per cent to 0·4 per cent, according to whether the machine is paralleled through bus-bars, transformers, overhead lines or cables. The smallest surge, therefore, occurs when the coupling switch is closed immediately at the moment of phase coincidence. The signal to actuate the switch should therefore be given in advance, that is, so much earlier according to the operating time of the coupling switch and the frequency deviation. An investigation leads to the following results: if with about 0·3 per cent frequency difference a synchronizing switch is closed so that the contact takes place at the moment of phase coincidence, there occurs between generator and supply a surge of about 30 per cent of the generator normal load. As a result of this surge, the frequency difference existing before synchronizing is corrected. This approximate value applies to the synchronizing of generators directly through bus-bars. If greater reactances lie between the generators, the surge decreases with otherwise equal conditions, but the oscillation lasts longer.

(*b*) Instant of Switching. The following simple calculation gives the correct instant in time. or the pointer position of the synchroscope, for the signal to operate in order to balance the switch lag, and for the synchronizing to be correct.

In a 50-cycle supply the pointer of a two-pole synchroscope, as in Fig. 176, with a frequency difference of 0·3 per cent, has a rotational speed of

$$N = 50 \times \frac{0{\cdot}3}{100} = 0{\cdot}15 \text{ Revs./sec.}$$

1 Rev./sec. = 360 electrical degrees per second. Consequently the electrical angular speed of the synchroscope is—

$$\omega = 0{\cdot}15 \times 360 = 48^\circ \text{ el/sec.}$$

In a two-pole synchroscope, the electrical degrees coincide with the geometrical angular degrees.

If, for example, the total characteristic switching time of the synchronizing switch amounts to 0·4 sec., the switch should be operated at the instant in which the rotating pointer of the synchroscope is in front of the "in phase" position by the angle—

$$\Delta\omega = 48^\circ \times 0{\cdot}4 = 20^\circ \text{ (approx.).}$$

If the switching time were 1 sec. instead of 0·4 sec., the angle at the instant of switching would amount to 50°. It can easily be judged that under such conditions reliable switching is impossible. If, on the other hand, the switching time amounts to only 0·2 sec., the angle is reduced to 10 electrical degrees and synchronizing is appreciably more certain.

The following three types of instruments are in general use for paralleling—

1. Rotating field synchroscope.
2. Phase voltmeter giving a sum voltage indication that is the so-called "lamps bright" switching.
3. Phase voltmeter with difference voltage indication, the so-called "lamps dark" switching.

The first instrument provides the best control and safety for the process of synchronizing.

Of the two schemes of connection of the phase voltmeter the "lamps dark" switching is preferable as regards precision on account of the possible voltage error near synchronism. (See Fig. 177.) It should be noted, however, that a fuse might blow or a bad contact occur, when the voltage would then also

be zero and on this account the synchronizing switch might be incorrectly closed. There are also automatic synchronizing devices which switch in on "lamps bright" but in addition have the precision of the "lamps dark" method.

(c) SUPPLY COUPLING AND LOAD HUNTING. The coupling of two loaded supply systems is generally much more difficult than pure parallel connection of a generator to a supply. Comparatively small switching inaccuracies cause even greater disturbance, since not only the moving masses of the generators

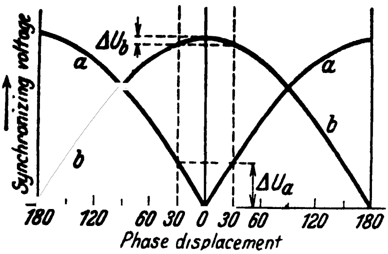


FIG. 177 SYNCHRONIZING VOLTAGE RELATIVE TO THE PHASE DISPLACEMENT OF THE LINE VOLTAGES

Curve *a*. With "lamps dark" switching
Curve *b* With "lamps bright" switching

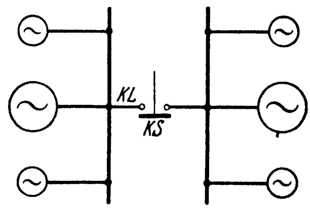


FIG. 178. PARALLEL CONNECTION OF LARGE SUPPLIES OVER WEAK INTERCONNECTING CABLES

KL Coupling cables
KS Coupling switch

but also those of the total connected load have to be accelerated or retarded.

If two supplies are paralleled through an inter-connecting cable of which the normal current is smaller than that of the smaller supply, the load conditions in the smaller supply are important for evaluating the surges arising in the interconnector. (See Fig. 178.) If the paralleling is not very precise, current surges may easily occur which reach the tripping out value of the protective relay on the coupling switch.

There may be extremely sensitive conditions with parallel connection in which the smallest surge may cause permanent load hunting until the nearest generator is finally isolated. There are various possible reasons for this.

1. A defect in the generator for example, an intermittent winding short circuit in the rotating field. Due to an overvoltage, caused in the rotor circuit by the stator current surge, an intermittent winding short circuit may arise at a weak part of the rotating field winding, and result in fluctuations of the magnetic field.

2. Too high regulating speed of the turbine governor which operates too violently on small speed variations.

3. Too small moving mass of the combined generator and turbine, which together with the characteristic of the turbine governor mentioned above, causes unsatisfactory operation. Water turbines behave particularly erratically in this respect under no-load conditions.

4. Large impedances between the interconnected generators and the remaining parts of the supply. While, as explained above, the wattless load distribution is very stable with large impedances, the opposite is the case as regards the stability of the load distribution. The reason for this is that the angle of displacement between the rotating field and the stator field increases in proportion to these impedances. This phenomenon consequently sets a limit to the value of the short-circuit impedance of the transformers.

It is not always possible to cure these various forms of hunting by adding damper windings to the rotating fields. The time of oscillation is generally too large, on which account as strong as possible a damper winding would be necessary which, from the constructional point of view, cannot be applied. In normal operation, load hunting also occurs on generators which are driven by reciprocating engines such as steam, diesel, or gas engines. In this case the trouble can often be remedied by building in a damper winding, since the frequency of oscillation is generally considerably higher than in the case of oscillations caused by the surges due to paralleling. (See Chapter X, para. 4.)

5. Generator Regulation when Feeding Open-circuited Overhead Transmission Lines. Unlike regulation with inductive wattless load which involves over-excitation, a capacitance wattless load on the generator necessitates a weakening of the excitation, since with capacitance loading the armature reaction has the effect of raising the voltage. It is necessary that the regulator shall be able to control the generator excitation in a stable manner down to zero, and an ordinary shunt exciter is no longer sufficient for this. To-day an exciter group is generally used consisting of a main and an auxiliary exciter. The excitation of the first is supplied by the auxiliary exciter, which can with advantage be maintained at constant voltage. The automatic voltage regulator can then without difficulty control the excitation of the main exciter to any desired value,

even including reversed excitation. The latter has no importance in the case of normal operation on load, since counter-excitation is only permissible to a very limited extent on account of the tendency of the generator to fall out of step. On the other hand, it has advantages as regards speed of regulation, in that due to the "negative impulse" in the exciter circuit the building up of the magnetic field is accelerated.

The difficulties associated with the switching in of long overhead lines are as follows.

When a generator is excited to give normal voltage for a transmission line, and this line is connected alone to the generator or its associated transformer, a sudden severe voltage rise is unavoidable. It will at least trip the over-voltage relay. A long overhead line should, on this account, not be directly connected but should be treated as described below.

1. The unloaded transmission line should first be connected to the unexcited generator and the rise of the voltage observed. With strong self-excitation this will be very marked, and the voltage at the open end of the line may be much greater than the working voltage after a state of equilibrium has been reached. In this case the line should not be set in operation.

2. If no self-excitation is apparent from the above test, it should then be decided whether the load current of the system can be supplied by one generator only, or whether several generators are necessary.

3. The regulating device of the generator, to be suitable for this connection, should enable stable regulation of the exciter to be obtained down to zero, or even to a certain negative value.

4. If a special generator is provided for charging the supply line and equipped with a suitable voltage regulating device, the line should be switched on to the unexcited generator and thereupon the generator gradually excited to normal voltage.

The transmission line is put under voltage even more safely if the line is connected on to the generator at standstill and the speed and frequency successively increased.

When several generators are necessary for charging the line, it is best to proceed as follows.

Generator No. 1 is excited with the smallest possible voltage with the automatic regulator in operation. Generator No. 2 is then paralleled in the usual way, its automatic voltage

regulator being first switched out. The excitation of No. 2 is adjusted as low as possible by hand so that it takes its magnetizing current principally from Generator 1.

If now the transmission line is switched in, no trouble is likely to arise if the magnetizing current of generator No. 2 has approximately the same value as the charging current of the line.

When several parallel generators are necessary for charging an unloaded overhead transmission line, none of these generators should under any circumstances be switched out. The remaining generators would not be able to supply the charging current for the line and give stable voltage regulation, and such switching out would result in a momentary over-voltage.

When an unloaded transmission line is to be isolated, the transmission line switch should first be tripped, and after this the generator switches.

If it is desired to proceed from the no-load to the load condition of the supply, the generator must first of all be changed to positive excitation; if the load is taken up by a generator with minimum or counter excitation, it will fall out of step.

More reliable and stable working of the transmission line is maintained if the transformers at the end of the line remain as far as possible continuously in circuit.

6. Load Transfer between Generators in Parallel. In modern installations, generators and their associated transformers are often solidly connected without an intervening switch. Troubles arising outside the group are then cut out by the oil switch on the high voltage side of the transformer. As compared with the older types of installation, this has the advantage of greater simplicity of the switch board and less breaking kVA. capacity for the oil switch, since this is limited by the transformer impedance. In order to bring about different transformer conditions inside the installation, there are usually isolating switches and an auxiliary bus-bar on the low voltage side between the generators and transformers. On to this bus-bar are generally connected the auxiliary plant of the power station, and even possibly a low-tension load. The operating conditions often require the loading of the low voltage side of one generator to be transferred to another without the parallel operation on the high voltage side being interrupted. The transposing is then done by means of the available isolating

switches as in Fig. 179, in which, under certain circumstances, it may be incorrectly assumed that when the generators are paralleled on the high voltage side and remain so, switching over can proceed forthwith. To remove the low voltage load from Generator No. 1 to Generator No. 2, the isolating switch *TII* is first closed and afterwards *TI* opened. As a result of this operation, however, a very severe arc may occur on opening the switch *TI*, which may easily lead to a short circuit on the bus-bar. The arc arises because on opening the isolating switch *TI*, the switching-out voltage occurring on its contacts is not always zero. This necessitates equal loading of both generators at the instant when the isolating switch is operated. When, for example, Generator No. 2 is heavily loaded while Generator No. 1 runs light, the voltage of Generator No. 2 immediately after opening the isolator is higher than that of Generator No. 1 by the amount of the voltage drop of its transformer.

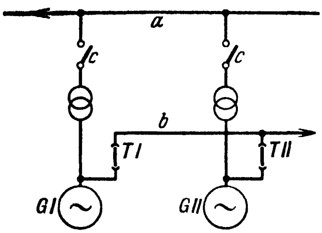


Fig. 179. Diagram of Connections for Load Transfer with Isolating Switches

a = High voltage bus-bar.
b = Low voltage bus-bar.
c = High voltage oil switch.
TI and *TII* isolating switches.
GI and *GII* generators.

To be able to switch over without danger, which also requires care, both generators should first be adjusted so that on the high voltage side their load and power factors are as nearly as possible the same.

7. Devices for Regulating Network Voltages. (*a*) Tapped Transformers. As a result of the closer and more comprehensive interconnection of supply systems, the supply of energy has become much more certain and the individual units, i.e. energy suppliers as well as consumers, have to a great extent lost their earlier independence as regards the maintenance of the voltage. This applies more particularly to the voltage conditions at the feeding points of the distributors.

A simple example might consist of a service area with several parishes supplied with energy, over a fairly long distance, from a main or substation. It is required that there shall be at the substation or at the distributing point a device for regulating the voltage, so that this is altered according to the load, that is, a compounding effect is required to maintain the consumers' voltage at a practically constant level. It is easy to perceive

that a main or substation coupled to other large power stations is not in a position to regulate its own voltage by adjustments to the actual generators. To balance the voltage losses between supply point and consumer, which fluctuate with the load, or the variations in the supplied voltage itself, induction regulators and tapped transformers are employed Since the latter, in most cases, solve the problem and are in addition appreciably cheaper than induction regulators they have in recent years been widely employed.

Voltage regulation with tapped transformers is generally done as follows. The regulating transformer has a main and a regulating winding with a number of steps. The regulating winding as a whole can be connected with the main winding so as to have the effect of raising or lowering the voltage. This gives twice as many regulating steps as there are tappings or switching steps. The change from one step to another can with modern tapped transformers be done on load with the assistance of protective resistances or choke coils. These limit the short-circuit current which occurs in the tapped coils with uninterrupted change-over from one step to another. The use of choke coils instead of pure ohmic resistances has the disadvantage of increased contact wear, since the coil circuit which has to be broken at each switching is chiefly inductive, which increases the work of switching. The longer duration of the arc with choke coils also endangers the main contacts of the tapping switch, which are only designed for sparkless operation, since the energy on breaking the circuit has partly to be handled by them.

With suitable designs the main contacts carrying the steady current always operate without sparking. The short-circuit load of the coils to be broken is taken up by specially formed sparking contacts which should not be placed in the transformer tank, in order not to foul the oil. Since the protective resistances or choke coils are only in use during the regulating process, they are not designed for continuous load.

If the operation does not proceed correctly, and the tapping switch remains in some position other than on a main contact, the protective resistance will be destroyed. This trouble should, however, be prevented by special mechanical interlocking on the driving mechanism.

If when tap-changing under load from one step to another a pronounced voltage drop of short duration is noticed, it is

probably caused by too large a protective resistance (or choke coil). In Fig. 180 (1) to (4) are shown the most important intermediate positions when tap changing without interruption of the supply

In the case of automatic tap changing transformers, the driving motor will continually move the tapping switch up and down if the sensitivity of the regulator is not made suitable, that is to say, if the regulator operates between the voltage

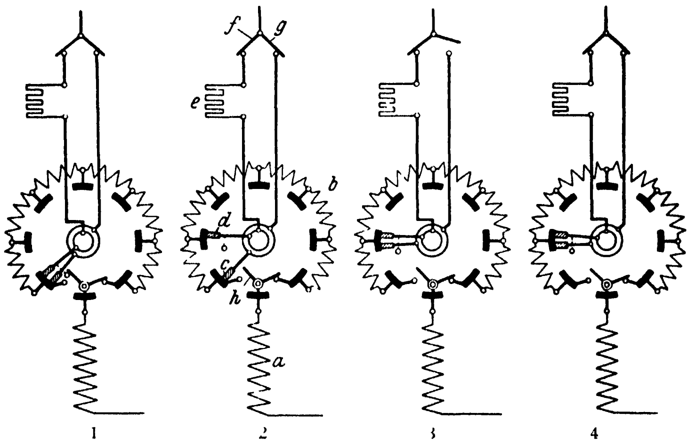


FIG. 180 SWITCHING PROCESS ON A TAPPED TRANSFORMER WITHOUT INTERRUPTION OF SUPPLY

1 Preliminary working position
2 Intermediate position, with one step of the regulator winding bridged over
3 Intermediate position Main current flowing through the protective resistance
4 New working position

a Main winding of the transformer
b Regulating winding of the transformer
c — Main contact of the tapping switch
d Auxiliary contact of the tapping switch
e Protective resistance
f Auxiliary arcing contacts
g Main arcing contacts

difference of two adjacent steppings If, for example, the step voltage is 1·2 per cent and the operating limit of the control is ± 0·5 per cent, the tapping switch will as a result be in a permanent state of movement.

(*b*) ROTATING TRANSFORMERS (INDUCTION REGULATORS). (See also Chapter XXIV) The voltage regulation with induction regulators is continuous, and on this account has a degree of precision which often exceeds the practical requirements. Induction regulators are often provided with devices which cut out the regulator and facilitate working without any voltage control. It should be noted, however, that in spite of

exactly equal voltages on the incoming and outgoing sides, the short circuiting cannot be carried out directly, since in induction regulators the two voltages mentioned are phase displaced as shown in Fig. 181 (*b*).

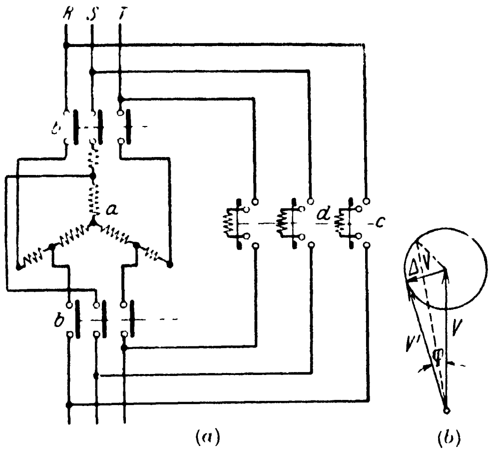


FIG. 181. BRIDGING OVER AN INDUCTION REGULATOR WITHOUT INTERRUPTION

(*a*) Diagram of connections. (*b*) Voltage vector diagram.

a Induction regulator.
b Isolator switch of the induction regulator.
c Bridging-over switch.
d Protective resistances or protective choke coils.
V Unregulated voltage.
V' Regulated voltage.
ΔV Differential voltage.
φ Angle of displacement of the two voltages.

If short-circuiting under load has to be carried out with uninterrupted operation, the two switches *b* in Fig. 181 (*a*) should be tripped out when the arcing contacts of the short-circuiting switch are touching. On the other hand, the main contacts of the latter should only touch when the two switches *b* have been tripped, that is, when the switching-out arc is completely extinguished.

CHAPTER XXXIV

CONTROL SCHEMES

1. Semi-automatic and Fully Automatic Equipment. Automatic control is to-day extending to such drives as pumping stations for public water supply, cable railways, hoists of all kinds, and the like. Such automatic plant is generally installed in remote places, and it is not always possible for the driving motor to have its own particular transformer, but the transformer plant for the whole district has to be utilized. On this account there is often, particularly with somewhat difficult starting conditions, a momentary voltage drop at the driving motor. This may be so considerable that various important control apparatus, chiefly shunt magnets, trips out. The voltage drops occur when the larger resistance steps of the starter are short-circuited with either separate rotor starters or centrifugal starters, due to the voltage drops in the transformer or the cables. Since, however, the first step in starting the motor is made, for example, by a float contact, which will not have altered its position during the attempted start, this will restart the motor, but the installation will for the same reason be switched out again, and so on. In modern automatic control gear this is usually taken into consideration, and control apparatus is reliable in operation even with voltage drops amounting to 25 per cent of the normal voltage. For safety, however, particularly of automatic plant, the minimum voltage should be arranged as low as possible, particularly since the working voltage itself may now and then be unavoidably low. Very often in automatic pumping stations troubles arise in connection with the float device, such as jamming of the float or contact troubles, but usually these are relatively simple to detect.

2. Ward-Leonard Control. The Ward-Leonard connection as shown in Fig. 182 consists of one or more d.c. motors directly supplied by a d.c. generator, frequently without a switch in the main circuit. The control of the motors is very finely adjustable, and adaptable for either direction of rotation as desired, by altering the generator excitation. If there is no switch with automatic overload trips in the main circuit, there

is a danger from self-excitation. Self-excitation causes the terminal voltage of the generator to rise and as a result the main current may increase to many times the normal, with the generator unexcited. In such a case the only cure is to stop the whole set immediately. Since self-excitation must be prevented from occurring under any conditions, the generator should either be provided with a reverse compound winding or its brushes should be slightly displaced out of the neutral zone in the direction of rotation.

If the machines to be driven by the motors have an appreciable inertia, as in the case of conveyors, overhead cranes and the like, a powerful reverse current may arise in the main circuit when the generator excitation is switched off quickly, which may amount to several times the normal current. The motor then operates as a generator, driven by the flywheel effect of the masses which are in full rotation, back on to the motor-generator set. This process is utilized in many installations, particularly conveyors, for braking purposes, with the help of suitable control gear.

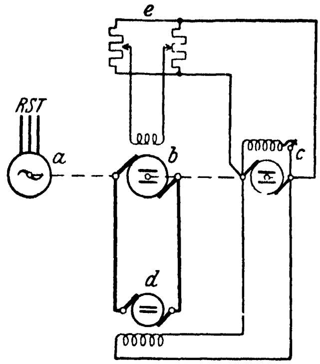


FIG. 182. DIAGRAM OF CONNECTIONS OF A WARD-LEONARD SET

a Driving motor
b — Ward-Leonard generator
c Exciter
d - Motor
e Field regulator

The speed control of a Ward-Leonard group is generally done with a potentiometer-connection as shown at *e* in Fig. 182.

The occurrence of excessive currents when stopping and when regulating the speed, even when the regulator is operated with care, may be due to wrong stepping of the resistance. After the regulating resistance has been adjusted to its zero position, a steady current of full load strength may sometimes exist. When the generator itself has no tendency to self-excitation, this current is not directly a source of danger to the group, but decreases the flexibility of control. It is caused by the excessive residual voltage of one exciter in the exciter circuit of the Ward-Leonard generator, usually the main exciter. It can be completely cured by breaking the exciter circuit of the main generator.

CHAPTER XXXV

PROTECTIVE SCHEMES FOR A.C. PLANT

1. Polyphase Protective Systems. In a.c. installations with no earthed neutral point, two current transformers only are sufficient for the tripping devices and will deal with all likely causes of trouble When the secondary windings are connected, for example, in the 60° connection as in Fig. 183, efficient protection is usually ensured against any short circuits between phases, provided the current transformer lies immediately in the faulty supply line, and that the fault current flows directly through it. If, however, the site of the short circuit is separated electrically, for example, by a transformer, from the place where the current transformer is fixed, even the 60 connection may fail, as shown in Fig. 184. With a short circuit on the high-tension side between two phases the sum of the currents formed in the relay circuit is equal to zero, and the relay will not operate.

A protective system which is reliable under any conditions is obtained by the use of three relays. This also protects against breakdowns to earth when the neutral point of the supply is earthed

2. Release Systems for Switches. Electromagnets are employed in practically all cases for the deliberate or automatic tripping of switches when trouble arises Three principal types of release systems exist, classified according to the manner in which the release magnet is supplied, and the type and mode of operation of the tripping process.

1. *No-volt Release.* The magnet attracted and supplied before release by a steady current is demagnetized by interruption of this current and trips when the voltage fails.

2. *Release by the Load Current* The magnet without current prior to the release is brought into action by the load current.

Load current systems are divisible into the following groups—

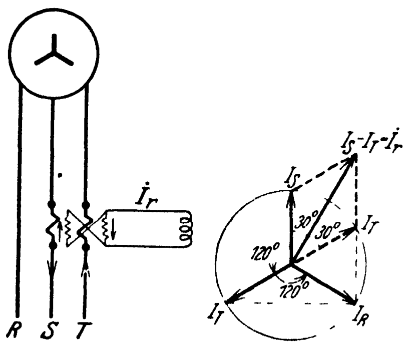
(*a*) Fed from the supply voltage.

(*b*) Fed from an external source independent of the supply.

(*c*) Fed through a current transformer in the associated supply.

(i) Steady Current System. This system (1 above) may

obviously only be used when a switch has to be released as a result of a drop in the supply voltage. In many cases, it has to be used for interlocking a switch which should not operate while the supply voltage remains switched out. It is used chiefly for the protection of motors against current surges which might arise after the supply voltage has remained off for a short time and then suddenly been switched on again. Even with voltage drops of very short duration, relays with



(a) (b)

FIG. 183. (a) PROTECTIVE CONNECTION WITH CURRENT TRANSFORMERS IN 60° CONNECTION. (b) VECTOR DIAGRAM OF THE CURRENTS

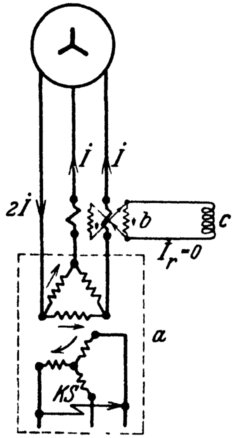


FIG. 184. CURRENT PATH ON FAILURE OF THE 60° PROTECTIVE CONNECTION WITH A SHORT CIRCUIT ON THE HIGH VOLTAGE SIDE *KS*

a Transformer Δ/λ connected.
b Current transformer.
c Protective apparatus (relay).

this type of operation may switch out the motor when this is neither desirable nor necessary. Where such interruptions are likely to be particularly harmful, either a time delay device should be incorporated in the no-volt release or the tripping voltage of the solenoids should be set lower. It can be seen from these considerations that the no-volt release can only be used for a few protective purposes, principally only for direct release of a switch when the supply voltage is interrupted. The no-volt release is in principle not suitable for a large group of switches when it has to be carried out with the assistance of the supply voltage. Its application for zero voltage release purposes is

then unsatisfactory, since with it all the switches are tripped, many unnecessarily due to the decrease in the supply voltage itself, instead of being released singly where required by the relay. No-volt release for the relays is only really satisfactory when the whole system is supplied from an independent auxiliary current source which remains unaffected by the failure of the supply voltage. Only those switches which are affected by the relays concerned are then tripped.

In machines which remain excited during starting—for example, synchronous machines—the terminal voltage falls proportional to the frequency. The inductance of a magnet decreases in proportion to the decreasing frequency and on this account, in spite of the decrease in voltage, the coil current remains approximately constant. The magnet remains attracted during the starting and only drops shortly before the machine is at a standstill. This behaviour of the magnet can be avoided by connecting a non-inductive resistance to the magnet coil.

(ii) Load Current System from Supply Voltage. This release system as in 2 (*a*) has in principle the same disadvantages as the zero-voltage release. The operation of a switch at will is impossible with failing supply voltage. The system is thus useless in the case of short circuits, where the supply voltage collapses.

(iii) Load Current System Supplied from Separate Voltage Source. The most reliable type of release is provided by using an auxiliary current source and the most dependable current source is an accumulator, which in practice is equipped with an automatic charging set in order that it shall always be ready for use.

The next best release as regards reliability of operation is tripping by means of current transformers. In this case the supply current is used directly for the release. This arrangement has advantages over 2 (*b*) in that it is much cheaper but has nevertheless a very high degree of safety which increases as the supply current increases in strength. The higher the current at the instant of failure, the more is the releasing magnet excited and its releasing power increased. Only the minimum releasing current sets a limit which condition, however, seldom arises, since this limit lies below the tripping value of the relay which operates the release. For switching processes to be undertaken at will, this type of release is obviously not suitable.

If this release process fails, almost the only cause is the insufficient load capacity of the relay contacts. (See Fig. 185.) With very high short-circuit currents there is excessive loading on these contacts, so that they either fuse or fail to break the arc.

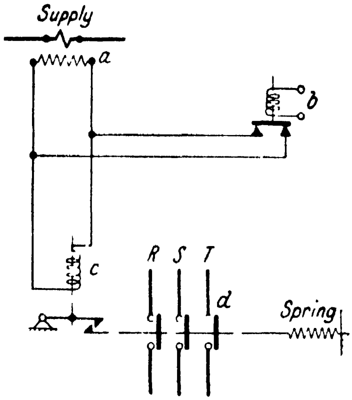


FIG. 185. SWITCH TRIPPING BY MEANS OF A CURRENT TRANSFORMER

a Current transformer *c* Release magnet.
b Protective relay of the switch *d* *d* Main switch

To obtain complete safety with this protective device the release magnet should not be supplied from an ordinary current transformer, but from an auxiliary current transformer. This should be so designed that it limits the rise in the secondary current to a value suitable for the contacts.

CHAPTER XXXVI

RULES FOR WORKING ON ELECTRICAL INSTALLATIONS

THE first point to be kept in mind is that no work should ever be done on any live part, however low the voltage concerned. If the person in contact with the live part is near rotating machines or other live parts, an involuntary movement may be made as a result of the stimulation of the nerves by the low voltage, and the operator may make contact with more dangerous parts. The result is generally an accident either directly or indirectly due to electricity.

The parts which may be touched should, after being isolated from the supply, always be earthed. The operator may also protect himself against the possibility of current being switched on from another source as a result of operations either wrongly carried out or else not properly understood, by fixing a permanent metallic short-circuit connection across all phases. This piece of metal should then be solidly connected with a good earthing conductor. There are to-day various special auxiliary devices which permit these safety measures to be carried out without touching live parts, an example of which is the earthing bar used by workers on outdoor plant. Earthing of the working parts is urgently necessary, when one realizes that even after complete isolation from the supply of the part of the installation concerned, it still may have a static charge, which will be conducted to earth by anyone touching it. On those parts of an installation where unexpected switching from another source is a practical impossibility, it is sufficient to fix an earthing conductor, which requires only a few seconds, thereby avoiding any danger of electrocution. When isolating from the supply the parts that are to be handled, it is very often assumed that the voltage is only coming from one side, for example, when one can dispose freely of the connections of individual generators. This, however, is in certain cases erroneous as shown by the following example. According to the position of the synchronizing transformer relative to the isolators and switchgear in the main supply conductors, the conductors between isolator and switch as shown in Fig. 186 may carry a very dangerous voltage. When the generator is under

voltage and the synchronizing switch 2 closed, the generator voltage is transformed through the one synchronizing transformer to the other transformer and thus to the main conductors connected with it. On this account it is always important to take care that the synchronizing transformer is completely isolated on both sides.

Accidents are also constantly occurring due to other mistakes. For example, work has to be undertaken on a generator

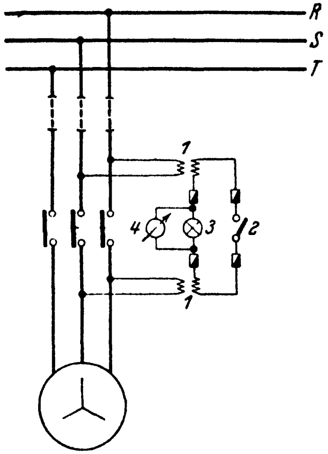


FIG. 186 DIAGRAM OF CONNECTIONS SHOWING VOLTAGE TRANSFER OCCURRING THROUGH SYNCHRONIZING TRANSFORMERS

(1) Synchronizing potential transformers (3) Synchronizing lamp
(2) Synchronizing switch (4) Synchronizing voltmeter

cable. For some reason it is not possible to shut down the generator, and in any case there is no isolator available. The workman wrongly concludes that he can safely proceed with the machine completely unexcited. The residual voltage, however, may be sufficiently high to be dangerous. Such a condition may be particularly risky when a transformer is connected with the generator, and work is to be done on the high voltage side. When cables are isolated it should not be forgotten that dangerous voltages may arise by electromagnetic induction from other live conductors, when the isolated parts are not short-circuited and earthed.

PART IV

MATERIALS

CHAPTER XXXVII

MATERIALS USED IN CONSTRUCTION

1. Failures due to Mechanical Stresses. After the pressing and drawing of metals and alloys certain stresses remain in them, varying according to how much treatment has been applied. These stresses may afterwards have serious effects when the

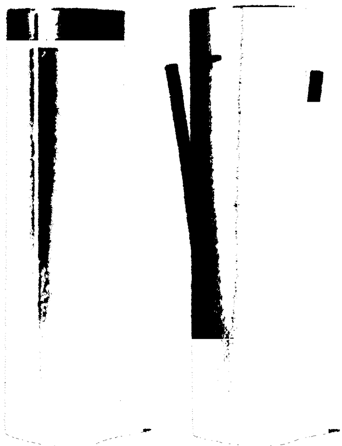


FIG. 187A. *Right:* STRESS IN COOLER TUBES EXHIBITED BY THE RELIEF METHOD. *Left:* COOLER TUBE AFTER HEAT TREATMENT TO ELIMINATE INTERNAL STRESSES

metal is in service. Several interesting phenomena associated with this type of failure are illustrated below by examples.

(*a*) STRESS CRACKS IN COOLER TUBES. When tubes are drawn, the outer layers of the tube walls are pulled with greater force than the inner layers. On this account, stresses exist in them if the material has not been properly heat treated before being put into service.

In Fig. 187A on the right-hand side is shown a cooler tube from which strips have been relieved to show the internal stresses. The piece of tubing on the left is taken from the same tube as before but has had heat treatment before being cut. It is clear that the internal stresses have been completely removed by this treatment. With this "relieving" method,

FIG. 187B. RELEASING OF STRESSES IN COOLER TUBES BY TREATMENT WITH MERCURY SALT SOLUTION

it is also possible to obtain information as to the amount of stress.

The stresses remaining in the material may often be very near the permissible limit, in which case with long spans, or due to minor external causes such as slight corrosion, abrasion and the like, longitudinal cracks may suddenly appear in the tubes. Coolers may also exhibit such cracks in service quite suddenly, since the temperature differences in oil and air coolers in themselves produce sufficient additional stresses. In Fig. 187B a further example is given to show the possible extent of the damage. The bare clean pieces of tubing were put into a weak mercury salt solution, and rapidly took the form shown. This latter test has proved very effective for the detection of

such stresses. It is equally applicable to more or less confined stresses of the type producing star-shaped cracks.

(*b*) SOLDER BRITTLENESS OR SOLDER FRACTURE. A phenomenon known as *solder brittleness* or *solder fracture*, which occurs with the mercury test when it is applied to hard drawn brass tubes, should be mentioned here. This may cause con-

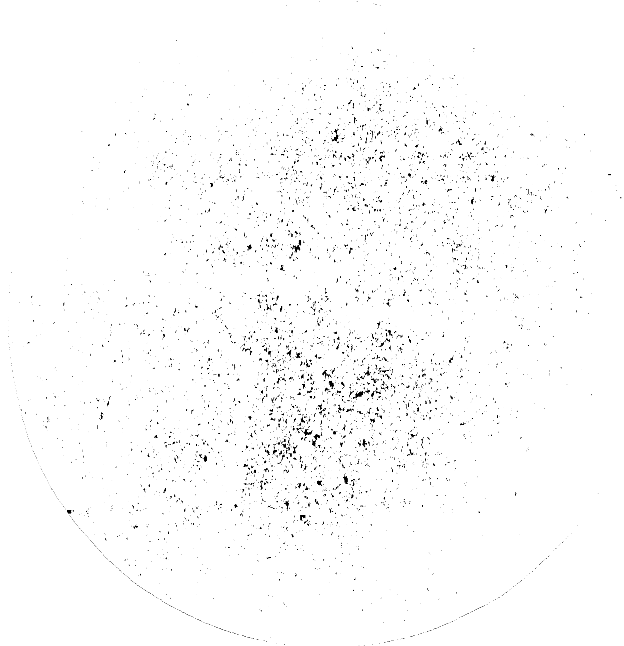


FIG. 188. SOLDER BRITTLENESS INGRESS OF FLUID SOLDER INTO SOLID METAL

The ingress has taken place from the left hand side

siderable damage. It has often been shown that a metal or alloy with internal mechanical stresses will become brittle or disintegrate on being brought into contact with any fluid metal. This phenomenon has been noticed in the course of mercury solution tests, in which the mercury plays the part of the fluid metal. If the material is brought into contact with liquid solder, the same thing occurs. The metal works its way in the smallest interstices of the solid material and so causes the crack. It can be clearly seen in Fig. 188 how the solder has filled the interstice on the left and damaged the material.

To complete this survey, an actual example is included which occurred in a workshop, which will demonstrate the practical effects of this phenomenon. On a rotating field a cast bronze short-circuiting ring was hard-soldered to brass bars. This soldering was done with silver solder, and after a few bars had

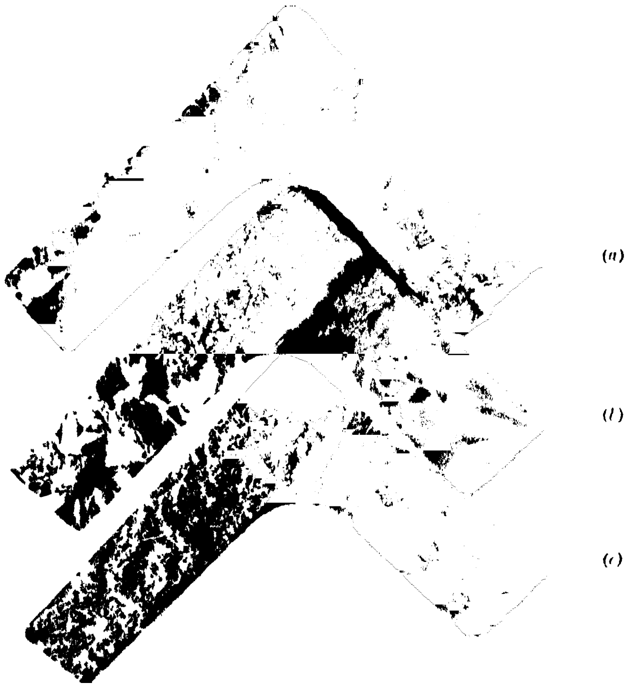


FIG. 189 SHORT-CIRCUIT RING FRACTURED DUE TO SOLDER BRITTLENESS

(a) Coarse grained, intercrystalline fracture caused by ingress of solder
(b) Adjacent place only partly fractured in the lower half of the left section
(c) Place near (b) normal shear fracture without ingress of solder.

been joined, a fracture appeared in the bronze ring. The surface of the fracture was extremely coarse and the fracture itself a pronounced fissure as shown in Fig. 189. This fracture occurred due to the fact that the places already soldered contracted with the brass bars, while the bars still being soldered expanded, which led to severe bending stresses. The applied liquid solder then caused solder brittleness in the parts under stress. In

Fig. 189 are shown three different places on the casting near the site of fracture. Fig. 189 (*a*), as already stated, is the fracture itself. At a place near the fracture there is only partial deterioration due to the solder and an associated intercrystalline fracture. (See Fig. 189 (*b*), left corner.) A deliberate cold fracture of the parts not yet damaged showed a fine shear fracture as can be seen in the upper part of the arm in Fig. 189 (*b*). That the difference in the fractures cannot be traced to the original structure can be seen from the right arm, where precisely the same construction as in Fig. 189 (*c*) is observable after suitable etching In Fig. 189 (*c*) an additional place is shown which is somewhat farther away from the site of the solder fracture. On the left arm can be seen a fine-grained cold fracture, and on the right the normal structure.

Care must always be taken during manufacture to ensure that metallic parts to be soldered are not brought into contact with liquid solder while under tension and heated during the soldering itself so as to result in unequal heat distribution and stresses. Unfortunately solder fracture has up till now received far too little attention.

(*c*) RECRYSTALLIZATION. If metals or alloys which are cold-worked to a certain degree are then heated for some time, a coarsening of the structure occurs which is called *recrystallization*. The maximum degree of recrystallization is reached when the original stress in the material has been removed to a certain extent, and is also dependent on the temperature. There is thus a fixed relationship between recrystallization temperature and degrees of stress. In connection with recrystallization, very brittle fractures often arise in the recrystallized zone.

The following is a practical example of this. With certain fan supports on motors brittle fractures often appeared at places for which there was no apparent reason. A microscopic examination showed that recrystallization was the cause of the phenomenon. In Fig 190 such a place is shown. The broken supports were cold bent before assembly and afterwards welded. At the bent places the conditions were conducive to recrystallization, which actually occurred when the heating took place during the welding. The start of this can be clearly seen in Fig. 190. From the illustration the cone-shaped compression and tension areas caused by bending the bar can also be observed. These phenomena can be prevented by careful heating

at high temperatures which must be above the recrystallization temperature, i.e. about 900° C.

2. Fatigue Fractures. It often happens that shafts or other machine parts which are continually exposed to alternating stresses suddenly break, although their steady breaking capacity is not nearly reached. This phenomenon generally occurs where a material undergoes alternating stresses between two limiting values, which exceed a certain amount, such as the steady or working capacity. After a certain number of load alternations, which depends on the extent to which the normal load is exceeded, the fracture occurs due to fatigue. The process leading to fatigue fracture may begin long before there are external signs, and without any obvious change at the place in question. The fatigue crack begins with a small fissure. Between the start of the fracture and the final break which leads to damage a long interval may occur. If in the interim the forces causing the overstress become less, the formation of the fracture is arrested. As soon, however, as the forces increase again, the fracture will progress further.

FIG. 190 RECRYSTALLIZED PLACE ON A FAN BLADE, CLEARLY SHOWING TENSION AND COMPRESSION AREAS

The appearance of a fatigue fracture surface is very characteristic. It is not in the least deformed, and exhibits in most cases a fine-grained structure. The disintegration at the surface of the fracture usually proceeds in various stages, through which the form of the fracture lines corresponding to the stress can be observed on the surface of the fracture. In the last phase of the damage, the so-called

ultimate fracture occurs, which may be clearly distinguished as regards appearance from the remaining fracture surface. Its surface is much more coarse grained. The last part of the material, which can no longer carry the stresses, suddenly fails, and consequently the break appears. In Fig. 191 is shown a fatigue break surface, in which on the left-hand side different fracture zones may be noticed. Fig. 192 shows the condition of the fracture surface very well. The darker coarse-grained part is the ultimate fracture.

The fracture is, as already stated, started by very small hair cracks which may be caused, for example, by machining. Such a hair crack operates like a notch. At the base of such notches a concentration of the stress distribution over the cross-section occurs with an increase of stress at the base of the notch, which may be enormous according to its sharpness. At this place the fatigue fracture begins, a fissure occurs, and this operates in the notch so that the separation proceeds over the whole cross-section. Even scratching with a steel scriber is sufficient to reduce the capacity 50 per cent or more. Fig. 193 shows the fatigue fracture of a motor shaft. The typical fracture features can be seen. The notch effect was in this case caused by a too sharply turned oil thrower. Sharp-edged cross-section variations also have the effect of a notch. If one wishes to prevent fatigue fractures with alternately stressed constructional parts, care must be taken that no sharp shoulders or grooves occur and that no sharp-edged cross-section variations are introduced in the parts of the machine concerned.

3. Bearing Metals. Bearing metals are usually chosen in practice from two groups of alloys, white metals and bearing bronzes.

(*a*) White Metal According to the operating conditions, white metal may be variously alloyed. In Table I below are collected the most commonly used standard alloys. In alloys containing much tin, the good properties of tin as regards soldering should be utilized. This metal diffuses well over the surface of the bearing shell and thus produces a good joint. To increase this process the bearing shells should be tinned before filling with bearing metal, and to achieve a thorough tinning of the shell a suitable soldering flux must be employed. A composition to be recommended is as follows: 40 per cent of zinc chloride, 1·4 per cent sal ammoniac, 0·85 per cent coarse salt and 57·75 per cent water. Further good properties of tin as a constituent of bearing metal are that it has a high heat capacity, and

FIG. 191. FATIGUE FRACTURE OF A MOTOR SHAFT

Right Fatigue breaks with fissures on the surface.
Left Ultimate fracture coarse grained with different fracture lines.

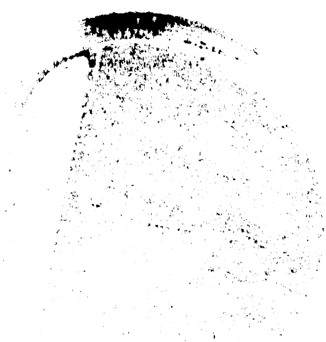


FIG. 192. FATIGUE FRACTURE OF A SHAFT

Right Fine grained fatigue fracture
Left First fatigue fracture, then coarse grained ultimate fracture.

during the cooling heats the shell in which the bearing metal is finally to be poured. On cooling the shell contracts, and holds the bearing metal more firmly. As a result of its good heat con-

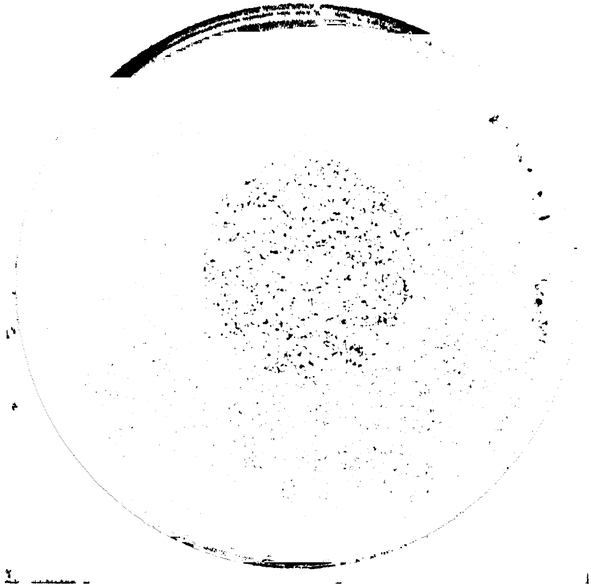


FIG 193 FATIGUE FRACTURE OF A MOTOR SHAFT

In the middle is the coarse grained ultimate fracture The fracture has progressed concentrically from the too sharply turned oil thrower

ducting capacity the tin also conducts away the frictional heat. To increase the hardness additional metals may be alloyed with it.

TABLE I

WHITE METALS FOR SLEEVE BEARINGS AND SURFACES
(According to German Specification DIN 1703)

Name	Symbol	Composition (per cent)			
		Tin	Antimony	Copper	Lead
White metal 80F	WM 80F	80	10	10	—
,, ,, 80	WM 80	80	12	6	2
,, ,, 70	WM 70	70	13	5	12
,, ,, 50	WM 50	50	14	3	33
,, ,, 42	WM 42	42	14	3	41
,, ,, 20	WM 20	20	14	2	64
,, ,, 10	WM 10	10	15	1·5	73·5
,, ,, 5	WM 5	5	15	1·5	78·5

Reproduction of these and the following standard specifications (pages 340 and 343) is with the approval of the German Standards Board.

By alloying the different metals as in Table I stable alloy structures are produced in the finished metal. Fig. 194 shows a photomicrograph in which the single elements can be easily seen. The alloy is WM.80 in the table. The more or less well-formed particles of the antimony and tin crystals can be clearly

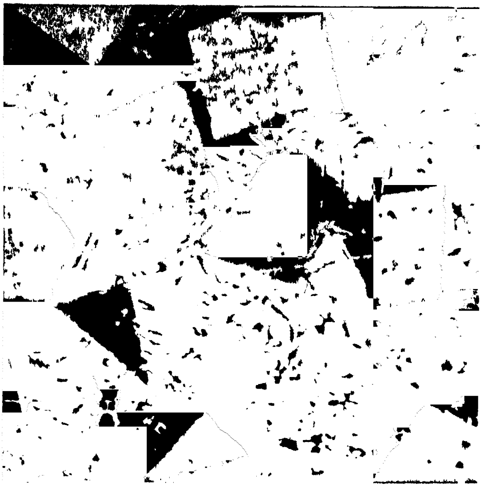


FIG. 194. WHITE METAL WM.80

White portions are mixed crystals of tin and antimony. Very small white particles are mixed crystals of copper, tin and antimony. Black ground is a lead and tin eutectic alloy together with tin.

distinguished embedded in a basic mixture rich in tin (black in the illustration). Near these can be seen the smaller scattered mixed crystals which in places show a needle formation. The latter can be even better seen in Fig. 195. This needle crystal portion has a consolidating effect on the basic material. The photographs show clearly that due to the different temperatures of solidification of the individual constituents the whole mass is not uniformly solidified, but that various combinations of the constituents predominate according to the degree of heating on melting and to the speed of the subsequent cooling. Mixtures may also occur in the more or less fluid basic mass due to the separation of single mixed crystals. The hard constituents which obviously form the bearing element in

white metals should not only be of a certain size but as far as possible evenly distributed over the bearing surface. Thus when melting white metals care should be taken that only very small admixtures occur. With bearing metals of high lead content, this may cause very unfortunate results, since the lead-containing group solidifies last. As can be seen from Table I, these alloys also contain very little copper, which prevents the formation of the copper-containing crystals which

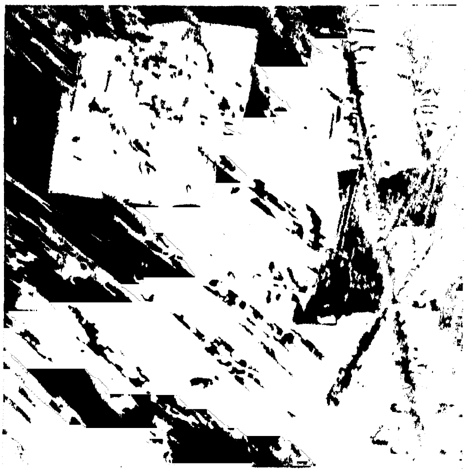


FIG. 195. WHITE METAL WM 80 AFTER SLOW COOLING.
White portions are mixed crystals of tin and antimony. Needle shaped white constituents are mixed crystals of copper, tin and antimony. Black ground is a lead tin eutectic alloy together with tin.

have a supporting effect. White metals are on this account only suitable for very low surface pressures.

The size of the hard particles is as important as their equal distribution, since this affects the running properties of the bearing. At the half fluid friction stage, that is, when film formation by the lubricant is taking place, the oil film forms more quickly when the crystals are large than when there are many small crystals. It can be assumed that when the bearing metal is coarse grained, its life is appreciably longer than when it is fine grained. The structure also affects the film-forming capacity. A coarse grain is obtained by high melting temperatures and slow solidification with a heated mould. It is not advisable, however, to make the grain too coarse, since it is

then liable to be brittle and exhibit unsuitable mechanical properties.

These considerations serve to show that for practical purposes the structure of a white bearing metal is much more important than its actual constituents. This, however, is only true within certain limits and one cannot compare, for example, bearing metal of high tin content with bearing metal of high lead content under any given conditions without taking other factors into consideration.

For some time attempts have been made to improve bearing metals of low tin content by certain hardening additions, keeping in mind the above requirements. Nowadays, it is found satisfactory to add metals with a high melting point to white metals of high lead content for hardening purposes, and nickel is one of the most suitable. The additional metal should naturally only be added in very small quantities, as otherwise the upper melting point of the alloy would be raised too much, which in turn would necessitate too high a temperature for melting the alloy so that individual components would be burnt.

When melting white metals, care should be taken to avoid too high a temperature of the metal bath. Excessive oxidization can be prevented by cleaning the bath with charcoal. There should be a certain relationship between bearing shell and molten metal temperatures, according to the construction and the thickness of the layer, in order to obtain the best running qualities in service. No general rules can be given for this.

(*b*) Bearing Bronze and Gun-metal. Gun-metals and bronzes used as bearing metals may be of very different composition. In Table II are given the most important alloys standardized in German Standards Specification DIN.1705/1. In addition, other special alloys are used in practice.

With these bearing metals also, the composition and melting and solidifying conditions affect the arrangement of certain components. With white metals the solidified metal tended to become more heterogeneous and the hard bearing constituent was embedded in a soft basic mass. In Fig. 196 is shown a fern-like formation, which may occur in certain bearing bronzes. The crests which can be seen are in this case also harder than the basic mass. The running-in of a bearing of this material consists in the grinding off of the harder raised

TABLE II

BRONZES AND GUN METALS

(According to German Specification DIN 1705 1)

Name	Symbol	Composition in				Used for
		Copper	Tin	Zinc	Lead	
Cast bronze 20	G Bz 20	80	20			Parts with much frictional pressure, e.g. spur gear bearings
Cast bronze 14	G Bz 14	86	14			Parts with much grinding, e.g. heavy duty bearing shells
Gun metal 9	Rg 9	85	9	6		Bearings for traction purposes
Lead tin bronze 10	Bl Bz 10	86	10		4	Bearings for electrical machines
Lead tin bronze 8	Bl Bz 8	80	8		12	Bearings with high surface pressure

portions It was formerly believed that in these alloys the composition ought to be as heterogeneous as possible but it is now certain that this has no appreciable effect on the running qualities of bearings In Fig 197 is shown a bearing bronze

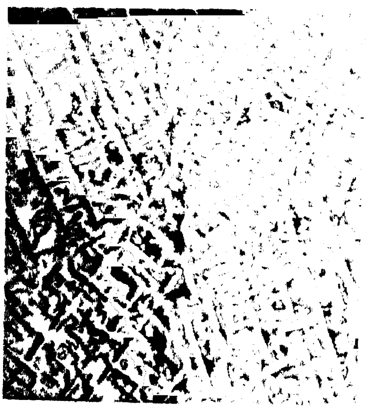


FIG 196 FERN-LIKE STRUCTURE OF A TIN BRONZE

FIG 197 BEARING BRONZE CONSISTING OF POLYGONAL MIXED CRYSTALS

corresponding to Bl Bz 10 in Table II This has a symmetrical construction consisting of polygonal mixed crystals

In Chapter XXXVIII the relationship between the bearing metal and the viscosity of the lubricant will be briefly discussed with reference to the latest theoretical considerations

In spite of the heterogeneous structure of the bearing metal, the bearing qualities may still be poor due to careless cold working, possibly even tearing, which produces an effect as in Fig. 198. The metal in this case is a lead-tin bronze of the composition Bl.Bz.10. It was damaged before being put into service and the soft constituents on the surface torn and afterwards smoothed over. This, however, did not make the

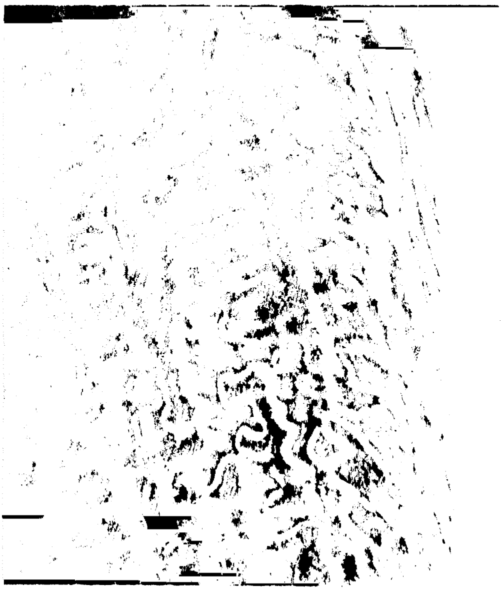


FIG. 198. BEARING BRONZE WITH A FERN-LIKE STRUCTURE, IN WHICH THE SURFACE IS DAMAGED BY BEING TORN

running surface sufficiently homogeneous and its properties were on that account very poor. It became pitted after quite a short time in service.

Another interesting case is shown in Fig. 199. In this instance, the bearing metal again has a fern-like structure in the basic material. On the running surface, however, there appears to be a layer containing lead. It must be assumed that due to overheating of the bearing as a result of the breakdown of the oil film for reasons that cannot be determined, the alloy has disintegrated and an easily melted portion has separated. The bronze contained a comparatively large amount of lead

and exhibited bad running characteristics. Since the interactions between bearing metal and lubricant are not yet fully understood, it is sometimes very difficult to determine the cause of these troubles.

When melting or casting this group of bearing metals, similar considerations apply as for white metals. The metal bath should not be overheated, and oxidization should be prevented.

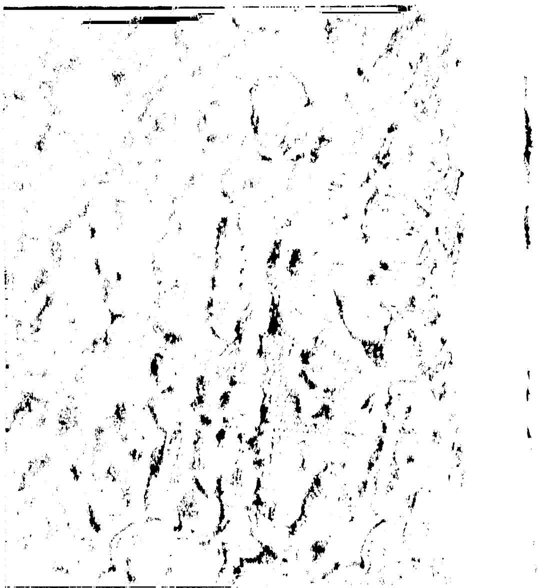


FIG. 199. BEARING BRONZE WITH FERN-LIKE BASIC STRUCTURE HAVING A MIXTURE RICH IN LEAD FORMING A LAYER ON THE RUNNING SURFACE.

If insufficient care is taken as regards oxidization, stannic acid is often found in the metal which may have a very bad effect. The expansion coefficients of the bearing shell and of the bearing metal should also be considered carefully. The differences between these two coefficients may be so large that the bearing seizes up and causes damage.

4. Solder and Soldering Processes. Metallic parts can be connected to one another by introducing between them a further metal or alloy in the liquid state, and allowing it to solidify. The process of connection consists of diffusion. The fluid metal

(solder) diffuses into the surfaces to be joined, and suitable solder should be chosen having regard to the demands likely to be made on such a joint. According to the new German Standard nomenclature, there are three different classes of solder--tin solder, silver solder, and hard solder. These different groups are distinguished not only by their composition but by their melting point. There is a fairly general impression that the melting point is of greatest importance as regards the stability of the soldered joint. It will be shown later that this is not the case.

Tables III, IV, and V show the different alloys standardized in Germany to-day

TABLE III

TIN SOLDERS
(From German Specification DIN 1707)

Name	Composition in		Used for
	Tin	Lead	
Tin solder 25	25	75	Flame soldering not suitable for carbon soldering
„ „ 30	30	70	Construction and coarse tin ware work
„ „ 33	33	67	Zinc plates and tin plates
„ „ 40	40	60	Brass and white metal soldering
„ „ 50	50	50	Brass and white metal soldering for electricity and gas meters
„ „ 60	60	40	Solder for easily melted metal objects. Fine soldering e.g. for electrical machines
„ „ 90	90	10	Where a sound joint is of particular importance

TABLE IV

SILVER SOLDERS
(From German Specification DIN 1710)

Name	Composition in			Melting Point C	Supplied as	Used for
	Copper	Zinc	Silver			
Silver solder 4	50	46	4	[illegible]	Grains	Soldering brass with 58 % or more of copper. For finer work when a cleaner soldered joint without subsequent machining is required as well as for soldering copper and bronze
„ „ 9	43	48	9	820	„	
„ „ 12	36	52	12	785		
Silver solder 8	50	42	8	830	Strips	
„ „ 25	40	35	25	765		
„ „ 45	30	25	45	720		

TABLE V

HARD SOLDERS

(From German Specification DIN.1711)

Name	Composition in %		Melting Point °C	Used for
	Copper	Zinc		
Hard solder 42	42	Remainder	820	Soldering brass with more than 60% copper
,, ,, 45	45	,,	835	Soldering brass with 67 % or more of copper
,, ,, 51	51	,,	850	Soldering copper alloys with more than 68%
,, ,, 54	54	,,	875	For copper, gun-metal, bronze iron band saws, etc
	Supplied in granular form			

Fig. 200A shows the typical eutectic structure of a so-called tin solder with about 35 per cent lead, magnified 100 times, and Fig. 200B shows it magnified 1 000 times.

FIG. 200A. EUTECTIC STRUCTURE OF A TIN SOLDER
Evenly fine grained solder

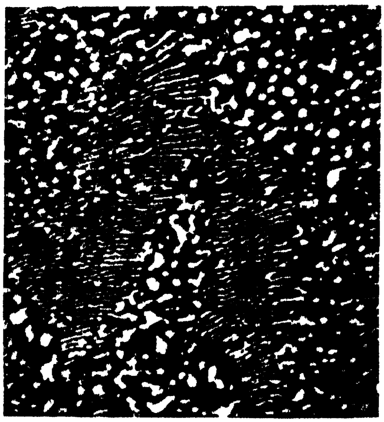


FIG. 200B. SAME SOLDER AS IN FIG. 200A MAGNIFIED MORE STRONGLY

In Figs. 201A and 201B a eutectic silver solder is shown magnified 50 and 500 times.

The diffusion process may take place in various ways according to the type of soldered materials and the solder used. The three most important types distinguished in this way are—

1. *Solder and soldered materials form mixed crystals.* An

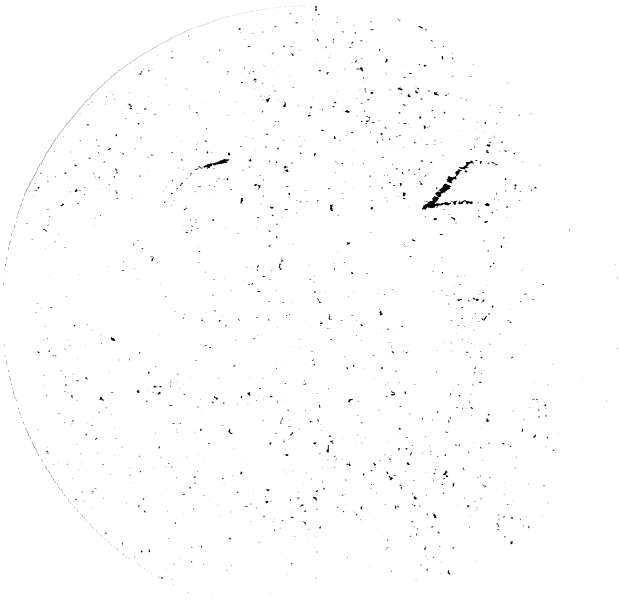


FIG. 201A. EUTECTIC STRUCTURE OF A SILVER SOLDER
Evenly fine grained.

FIG. 201B THE SAME SOLDER AS FIG. 201A MORE HIGHLY MAGNIFIED

example of this is the hard soldering of copper with brass spelter. The diffusion may proceed so far that the solder no longer makes a connection but new alloys form. Such soldered joints are naturally very sound mechanically and in addition, resistant to corrosion due to the mixed crystal formation. The alloy may exhibit quite different characteristics mechanically from the solder itself, so that it is not possible to express an opinion on the joint, based on the mechanical strength of the solder.

The same applies to the melting point. The mixed crystals which form may have a different melting point from that of the solder, so that the melting point of the solder is not that of the joint.

2. *Solder and soldered materials form an intermediate type of crystal* as, for example, in the soft soldering of copper with tin solder. Here also there will probably be a union between solder and soldered material. These joints are not nearly as good as those in Group I.

3. *The solder will only dissolve the soldered material when it is in a molten condition.* The alloy thus formed reverts to its original constituents on cooling. An example of this is the soldering of zinc with tin solder. The alloy formed may be eutectic which is an advantage, since the low melting point of the eutectic facilitates the diffusion of the solder into the soldered material. Good mechanical joints can be made in this manner. Since, however, different metals occur near to one another at the soldered place, local electrical action may occur and the soldered place is subject to corrosion. These joints are not so good as those in the first category as regards corrosion.

If, when soldering, the diffusion does not proceed far enough on account of the particular soldering process, the joint may still be improved by subsequent heat treatment to increase the diffusion. When a joint of high mechanical strength is required, such a subsequent heat treatment is always advisable.

It has already been mentioned that too much reliance has been placed upon the melting point as a means of judging the correct solder for use in any particular application. Owing to the formation of mixed crystals and of eutectic mixtures between the solder and the soldered material, alloys are produced which behave quite differently from the solder as regards temperature. This difference is even more marked when

the joint is subjected to long periods of overheating in service. According to the type of union, the soldered joints may soften quite differently, and finally even flow, under continuous load. In such cases, no conclusions can be drawn from the melting point of the solder. It has often been shown that the heat caused by continuous stresses may cause solders with high melting points to flow at much lower temperatures than solders with low melting points. Under such conditions, the continuous capacity of the joints concerned should be investigated before they are used on machines or apparatus.

A layer of oxide may form on the soldered piece as well as on the fluid solder during soldering. To improve the joint, certain materials should be used which either melt and cover up the metallic parts and so keep out the air, or else exert a reducing effect on the oxide. The composition of these materials is dependent on the soldering temperature. For soft soldering powdered resin and pieces of sal ammoniac are generally used. Very often chloride of zinc is used with sal ammoniac. "Soldering flux" also contains the same constituents but dissolved in water. When in the form of soldering pastes these materials are mixed with some bonding powder or with grease. Borax powder is chiefly used for hard soldering. Various borax salts can also be used, for example, soldering powder containing boracic acid or "metaborate."

Care should always be taken, when soldering parts of electrical machines and apparatus, that none of the soldering material comes into contact with the insulation, which might either be directly damaged by it, or else absorb the salts and so become saturated with electrolytes which, being hygroscopic, are good conductors. Lack of care in this respect is a much too frequent cause of trouble.

Care should also be taken to ascertain that the metallic parts to be joined are not stressed, since the fluid solder may make the soldered part brittle, as described in para. 1 above.

5. Corrosion in Cooler Tubes. The tubes used in oil and air coolers for transformers and generators are made almost exclusively of brass. As a rule two alloys are used for this purpose with the following composition: 70 per cent copper, 29 per cent zinc, 1 per cent tin; 63 per cent copper, 37 per cent zinc. It may happen that for various reasons the tubes are attacked in a relatively short time by corrosion.

The corrosion of brass tubes is associated with their crystal

Fig. 202 Structure of a Cooler Tube
Alloy of 70 per cent copper 29 per cent zinc and 1 per cent tin (pure α structure)

Fig 203 Selectively Corroded Cooler Tube (Pure α structure)
Dezincification on the right hand side of the illustration

structure, with the heat treatment during manufacture, and with certain working conditions. It has often been asserted recently that the first alloy is non-corrosive, and that it should therefore be standardized. It must be emphasized that this assertion does not agree with the facts. The structure of such tubes consists of α-mixed crystals as illustrated in Fig 202. If now at any place on the tube due to insufficient heat treatment certain mixed crystals are only incompletely recrystallized, and certain internal stresses appear in connection with them, then a potential difference immediately arises at this place which leads to damage of an electrochemical type on the introduction of a suitable electrolytic fluid. (Obviously such local effects may also arise in other ways.) When the right conditions occur, copper and zinc ions of the base structural components go into solution, and the copper is immediately released. This causes the phenomenon known as *dezincification*, which can be seen in Fig. 203 on the right of the illustration. The "copper plug," owing to the way it is formed, is very porous and in time it weakens, and may be washed away by the flowing liquid, and cause marked local corrosion as illustrated in Fig. 204, such that finally actual holes form. The phenomenon is associated with certain places in the tube, and is called *selective corrosion*. It is often very difficult to determine its precise cause.

FIG. 204. CORROSION OF A COOLER TUBE
Due to the partial breaking away of the copper plugs rapid corrosion is occurring

The second alloy, consisting of 63 per cent copper and 37 per cent zinc, is associated with that part of the copper-zinc diagram in which, with incorrect heat treatment, α- and β-mixed crystals may occur together. In Fig. 205 such a mixed structure is shown. The light portions are the α-mixed crystals and the dark ones the β-mixed crystals. The β-mixed structure in this range only occurs under specially bad conditions. It is

classed as a transition structure and is therefore very unstable. There is in this case an appreciable base potential from the α-constituent, which forms a local element in the presence of an electrolytic fluid. The process already described above occurs first on the surface. The β-component loses its zinc and its place is taken by a porous copper plug. In this way the trouble may spread farther and farther towards the inside of the tube, until there finally remains only a sieve consisting of α-particles.

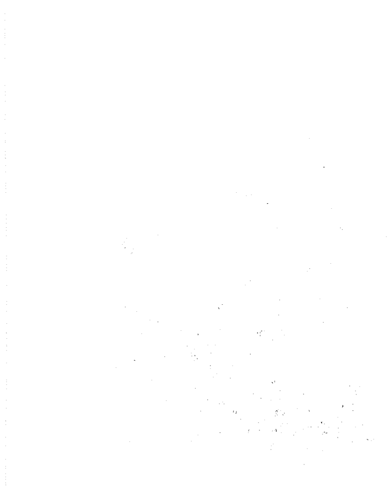


FIG. 205. MIXED STRUCTURE OF A COOLER TUBE WITH $\alpha + \beta$ MIXED CRYSTALS. WRONG HEAT TREATMENT

The light places are the α-mixed crystals and the dark the β-mixed crystals.

This condition is shown in Fig. 206. From this photomicrograph it can be seen that instead of the black β-components there are small copper plugs. We are therefore dealing in this case with general dezincification, and it is obvious that the tube has lost all mechanical strength as a result of the sieve formation.

In addition to this process the selective corrosion first described may be occurring simultaneously, leading to the formation of large local copper plugs. Such a case is shown in Fig. 207 on the right-hand side.

Lack of knowledge of these facts has led to the belief that the alloy 63 per cent copper, 37 per cent zinc is not so reliable, since it has a tendency to lose its zinc. It should be emphasized here that this does not agree with the facts. With proper

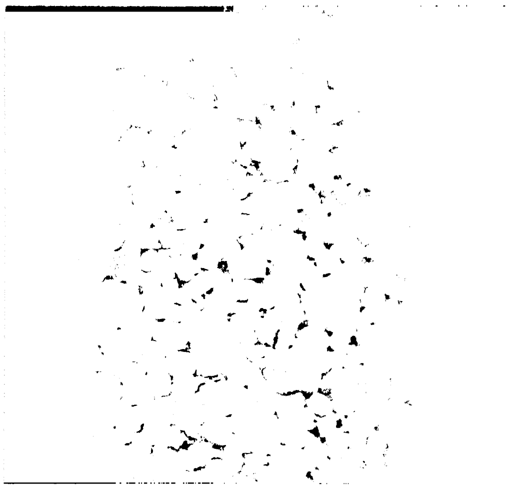


FIG. 206. GENERAL DEZINCIFICATION IN A COOLER TUBE THAT HAS $\alpha + \beta$ MIXED STRUCTURE DUE TO WRONG HEAT TREATMENT

The dark β-mixed crystals are partly broken down by porous copper plugs

FIG. 207. DEZINCIFICATION AND SELECTIVE CORROSION OF A COOLER TUBE OF $\alpha + \beta$ MIXED CRYSTALS

heat treatment, it is possible to give this alloy a good structure, not having these properties, and behaving precisely the same as the first alloy containing tin. The user of these tubes should therefore, for his own protection, allow an expert to make a number of tests before they are assembled. Selective corrosion, which under different conditions may be started solely by local electrolytic action, cannot be prevented by these measures. It may be that the cooling water itself is causing the corrosion, due to its composition. There is also the possibility that the reaction between certain constituents of the water and the metal may form secondary reaction products having a protective effect on the tube surface. Occasionally, however, even these products accelerate the corrosion. For these reasons it is always very difficult to explain corrosion phenomena, even when the conditions are such as to be likely to lead to corrosion. If the flow of water in the tube is made turbulent due to the deposition of scale, additional erosion effects may occur, which obliterate the signs of the corrosion.

Corrosion of another kind may occur in the case of liquid starters. (See Chapter XXVIII, para. 3.) This is usually in connection with the rusting of steel parts due to insufficient protection. Since soda is generally used in liquid starters, adequate protection can only be given by applying a coating of some material which resists alkalis. If chloride is present in solution, electrolysis is greatly accelerated, so that care should be taken to ensure that the soda as well as the water contains the least possible amount of chloride.

Light-weight metals have become more and more popular recently in the construction of electrical machines and apparatus. It is now common knowledge that the contact of aluminium and similar light metals with steel, particularly in open air plant, may result in marked corrosion. If the light-weight metal is covered with a protective layer, the steel parts connected to it may be endangered by this layer. One method which has been found very satisfactory in practice, for giving a sound metallic connection, is to place a piece of cadmium leaf between the light-weight metal and the steel.

Stray currents or bearing currents may also bring about corrosion. These can be cured and the danger averted by quite simple methods, generally by suitable insulation. (See Chapter VII, para. 2.)

6. Scale Formation in Cooler Tubes. In all cooling systems

in which water is used as a cooling medium, there are depositions of more or less soluble salts which form what is generally known as *scale*. This scale prevents the transfer of heat and in some circumstances may be highly dangerous. Up till now it has been erroneously believed that scale consisted of separated calcium carbonate (chalk). Recent experiments have shown, however, that boiler scale is not one uniform product but may contain different salts. The gypsum content of the water is an important factor, and the principal constituents of the scale are undoubtedly gypsum and chalk, but in addition there may be present silica, magnesium, clay, iron salts, chlorides, and sulphates. In certain waters there are also considerable quantities of organic material dissolved, which may affect the deposit of scale. The crystallate from the cooling water often forms layers between the other deposits, so that it is obviously unwise to draw conclusions as to the composition of the scale based on analysis of the water.

Certain relationships, however, can be established if instead of the usual data of the water analysis, quotients are used, for example--

For the water.

$$\frac{\text{Gypsum hardness}}{\text{Carbonate hardness}} \quad \text{hardness quotient.}$$

$$\frac{SiO_2}{CaO} = \text{silica quotient.}$$

$$\frac{MgO}{CaO} = \text{magnesia quotient.}$$

For scale.

$$\frac{CaO\ (\text{contained in } CaSO_4)}{CaO\ (\text{contained in } CaCO_3)} - \text{hardness quoteint.}$$

$$\frac{SiO_2}{CaO} = \text{silica quotient.}$$

$$\frac{MgO}{CaO} = \text{magnesia quotient.}$$

Since these quotients are pure comparative numbers, both for the water and the deposit, they can be compared with one

another. When considered in the reciprocal relation they give a clear picture of the scale, and allow certain conclusions to be drawn as to its components.

The heat conducting capacity, and therefore the heat transfer of different kinds of scale, varies with the composition and thickness. A stony deposit consisting of gypsum has the best heat conducting capacity. Pure chalk scale, with about the same thickness as gypsum, has a heat conducting capacity not nearly so good. Deposits containing silica are the least desirable in this respect. They have approximately the same heat insulating effect as a layer containing chalk or gypsum twenty or thirty times as thick.

These scaly deposits in the cooling system (see Chapter XXII, para. 3) should be periodically removed with hydrochloric acid. The acid should not, however, be allowed to remain too long in the tubes or it may corrode them. After removing the acid it is advisable to neutralize any residue with alkali, although thorough washing out with water will probably serve the purpose.

The cooler tubes may also be stopped up with eroded matter as well as with scale. As long as deposits of this kind are not jammed together, it is generally possible to clean the tube by reversing the flow of water in it.

The cooling water may produce certain corrosive effects as well as scale, which are briefly described in para. 5 above.

In oil coolers a part of the sludge formed by the deterioration of the oil in service occasionally settles on to the cooler tubes. Sometimes this external deposit may be of such a form as to affect the heat transfer very adversely. A layer of sludge has just as bad an effect as a layer of boiler scale five times as thick. Further information regarding the decomposition products of oil is given in Chapter XXXVIII, para. 1, and Chapter XXXIX, para. 5.

CHAPTER XXXVIII

LUBRICANTS

1. Lubricating Oils. Mineral oils are generally used to-day for the lubrication of electrical machines. They are usually mixtures of hydrocarbons freed from hard portions by distillation and subsequent refining, and of different degrees of viscosity according to the use to which they are to be put. Formerly, the study and choice of a lubricant, based on the hydrodynamic theory, was only concerned with finding an oil of suitable viscosity. Exhaustive study of the lubricating process has now led to the conclusion that other properties should be taken into consideration when judging the lubricating capacity. The latest ideas on boundary surface phenomena and X-ray examination have been applied to determine the structure of the oil film, and it has been shown that certain reciprocal chemical reactions actually occur between the lubricant and the bearing metal. If the best lubrication is to be attained, these two elements must be suited to one another. (See Chapter XXXVII, para. 3, "Bearing Metals.") The molecular process plays a large part in the period of "half dry" friction on starting up and slowing down, and the hydrodynamic laws no longer apply to the lubricating film. A lubricant should therefore be of high film-forming capacity, so that the period of half-dry friction is as short as possible. The oil film should be enduring, and not easily broken once it is formed.

Although there are numerous lubricants on the market, only the following two groups of mineral oils can be considered suitable for electrical machines (excepting steam turbine equipments).

1. For machine bearings in which

$$P \times v < 50 \frac{\text{kg.}}{\text{cm.}^2} \cdot \frac{\text{m}}{\text{sec.}}, \text{ Group I is suitable.}$$

2. For machine bearings in which

$$P \times v > 50 \frac{\text{kg.}}{\text{cm.}^2} \times \frac{\text{m}}{\text{sec.}}, \text{ Group II is suitable.}$$

Were P = Projected bearing pressure; v = Journal speed.

PROPERTIES OF OILS IN GROUP I

Kind of oil	Refined
Specific gravity at 20° C.	Not over 0·94 (not specially important)
Flash point in an open crucible	Not under 150° C.
Solidification point	Not over 0° C. for indoor use Not over − 15° C. for outdoor use
Content of mineral acid	0
Viscosity at 20° C.	Not over 25° E.
Viscosity at 50° C.	2·5°-3·5° E.
Asphalt content	0
Fatty oil content	Normally = 0
Ash content	Maximum 0·02%

PROPERTIES OF OILS IN GROUP II

Specific gravity at 20° C.	Not over 0·95 (not specially important)
Flash point in an open crucible	Not under 175° C.
Solidification point	Not over 0° C. for indoor use Not over − 15° C. for outdoor use
Content of mineral acid	0
Viscosity at 20° C.	Not over 60° E.
Viscosity at 50° C.	6-7° E.
Viscosity at 80° C.	Not under 2° E.
Asphalt content	0
Fatty oil content	0
Ash content	Maximum 0·02%

It can be seen from these two summaries that the lubricant for bearings for open air plant, such as cranes, should be less sensitive to cold and have a correspondingly lower solidification point. It has been suggested from various sources that fatty oils should be added to the mineral oils to raise their lubricating capacity, since they increase the film-forming characteristics. In this case the rules for acid content given above should be suitably altered. These mixed oils, however, should be applied with care, since additions are often used which have the desired properties to begin with, but after a short time exhibit unsuitable secondary characteristics.

In special applications, for example, steam turbine plant where the same lubricant is used for turbine and generator, the oil must satisfy very stringent requirements, both in regard to its resistance to high temperatures and in the event of entry of steam. It should also be unaffected by certain constituents, caused by the hardness of the water, which may pass into the steam. If at these high temperatures the oil comes into contact with atmospheric oxygen, it will decompose with the evolution of partly soluble acid products. Products of oxidation also

occur which are not soluble in warm oil, and which are known as *asphalt products.* The two latter are deposited in the oil cooler, and may reduce the efficiency of the cooling system very considerably, more especially as they are poor conductors of heat, in which case the oil is still further heated and rapidly deteriorates. Suitable oils for turbo sets can, therefore, only be chosen within certain narrow limits. The Brown Boveri Co.'s standards for turbine lubricants are set out below. Further recommendations are contained in *Rules for Judging Lubricants* set up by the Swiss Association for testing materials (SVMT.17).

PROPERTIES OF TURBINE LUBRICANT

Kind of oil	Refined
Specific gravity at 20° C.	Not over 0·94 (not specially important)
Flash point in an open crucible	Not under 165° C.
Solidification point	Not over − 5° C. (With suitable temperature conditions higher values are permissible)
Viscosity at 20°	Not over 30° E.
Viscosity at 50°	Between 3·5 and 5·5° E.
Viscosity at 80°	Not under 1·5° E.
Mineral acid content	0
Fatty oil content	0
Ash content	Not over 0·01%

Tests for degeneration of lubricant should give—

Saponification factor	,, ,,	2·0
Sludge content		0%

Steam Jet Test.

Emulsification in distilled water	0 cm.³
,, 1% soda solution	0 cm.³

The phenomena referred to as degeneration of turbine oil may, of course, take place in the two kinds of oil mentioned before, although it is not very likely, as the working temperatures are so much lower.

When lubricating oils which have not been properly refined are used, hard products may form and spoil the oil film, even at quite low temperatures. As this alteration proceeds, certain acid reaction products also form, which may lead to the corrosion of shafts. On the other hand the shaft materials will not be corroded with the usual operating conditions even with comparatively high acidity, as long as it is not mineral acid. Generally quite different processes associated with degeneration

due to oxidation cause shaft corrosion. In steam turbine sets, there is also the danger that the lubricant will alter more quickly due to continuous contact with the metal of the cooling tubes. It should be remembered, however, that the temperature in the oil cooler is usually so low, and the speed of flow so great, that it very rarely has a bad influence.

It may happen that certain oils with a special capacity for absorbing air become saturated with this in operation. All mineral oils have a comparatively large capacity for absorbing air. The dissolved oxygen may produce unstable products of oxidation, which on breaking down cause secondary corrosion of the metal, or alternatively, saturated oil-air mixtures may be introduced into a machine part under low pressure, so that a part of the dissolved air escapes and causes cavitation phenomena. These phenomena are most likely to occur when oil is used for the purpose of excluding air under high pressure. The escape of air from the oil may also cause very undesirable noises, and in some conditions quantities of foam may form. This foam is not very dependent on the quality of oil used, always provided that the properties of the oil satisfy the basic requirements. It is much more likely to be caused by the special operating conditions which allow the oil to become saturated, or even over-saturated, with air which later escapes.

The acid content is no criterion of the corroding properties of a lubricant, since it is only concerned with the proportion and not the nature of the acids. Different acids, however, cause different degrees of corrosion. The degree of saponification is just as little use as a measure of the alteration of an oil, since the saponification factor merely shows how much material that can be saponified with an alkali is contained in the oil. Determination of the saponification has recently been carried out on different lines to determine clearly the degree of degeneration and the amount of use still to be expected from the oil. Some warning is, however, advisable regarding the general application of this practice. There are various properties of great importance when deciding on the suitability of an oil for service, for example, emulsifying property and foam-forming capacity, which are closely associated with the saponification. According to the author's view no opinion as to the behaviour in service of mineral oils can be safely based on the usual analytical method of testing. For this purpose technological methods are much more suitable.

2. Lubricating Greases. For machine parts which are difficult of access and for ball and roller bearings, greases are used for lubrication as an alternative to mineral oils. These are usually solutions of calcium or soda soaps in mineral oils and they always contain a small quantity of water. Other constituents are grease which has not been saponified, glycerine, free chalk and, in the case of cheaper products, loading material. The following table summarizes the requirements which should be fulfilled by a good machine grease.

PROPERTIES OF GOOD MACHINE GREASE

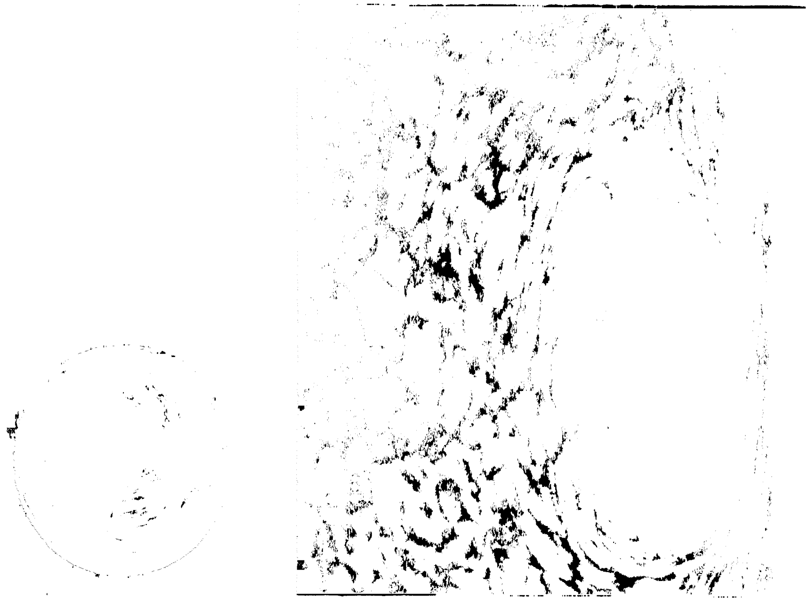
Kind	Fixed mixture of soap and mineral oils
Melting point	Not under 75° C. for light greases; Not under 65° C. for dark greases
Ash content	Not over 4%. At higher ash contents the grease must be considered as "loaded" if the soap content is below 25%
Acidity	Not over 1%. For ball and roller bearing greases only pure mineral lubricant must be used
Content of mineral oil	Not under 70%.
Water content	Not over 4%. Higher with emulsion greases
Content of foreign matter	Not over 0·5%. No scratching or grinding constituents are permissible
Homogeneity	With a thin section between two glass plates no separation of constituents should occur
Content of colouring matter	Only greases exhibiting their natural colour should be used since the addition of colouring matter usually spoils the lubricating properties

For roller bearings of the type used on tramways, greases with high melting points and approximating to the following specification should be used.

PROPERTIES OF HIGH MELTING-POINT GREASE

Kind	Fixed mixture of soap and mineral oils
Incipient melting point	Not under 120° C.
Dropping point	Not under 140° C., but this may be lower for tramway motors
Acidity	Not over 1%
Ash content	Not over 4% when the soap content is below 25%
Water content	Not over 0·5%
Content of fixed foreign matter	Not over 0·5% and containing no scratching or grinding materials
Homogeneity	On heating three times to the melting point and subsequently cooling, the individual constituents should not separate

If solid greases are not homogeneous, or have too great a proportion of calcium soap, serious troubles may occur, especially with ball and roller bearings. Due to the kneading effect in the bearing, the oil will be pressed out of the grease, and the soap alone remain. This, however, will no longer lubricate, high temperatures occur and finally the soap will char. The



(a) (b)

FIG. 208. TORSIONAL FRACTURE OF THE SHAFT OF A TRAIN LIGHTING DYNAMO, CAUSED BY STICKING OF THE BALL BEARING

(a) Torsion fracture surface
(b) Photomicrograph of part of the shaft with torn surface and inclusion of foreign matter on the right-hand side

balls or rollers and their cages may be severely pitted by this mixture. The overheating may also cause the shaft to jam and to be damaged by torsion effects. In Fig. 208 such a case is shown The machine in question was a train lighting dynamo. Fig. 208 (a) shows clearly the torsion fracture surface, and Fig. 208 (b) is a photomicrograph from which can be seen how great may be the displacement of the material in such cases. On the surface of the shaft direct folds were formed in a few places in which a mixture of oxides and dirt collected.

Such a fold is shown on the right-hand side of Fig. 208 (*b*) with its accumulated matter. The balls and cage of the bearing were very pitted and covered with completely charred chalk soap.

When grease has to be used out of doors, for example, in open air switching plant, it should not contain any calcium soap, or else in the winter soap separation may occur and lead to sticking and similar troubles to those mentioned above and in Chapter XXV, para. 3.

CHAPTER XXXIX

NON-ELECTRICAL TROUBLES IN INSULATING MATERIAL

1. Fibrous Materials. The various fibrous materials are used in different forms for insulating material, either as spun threads, woven material, paper or pressboard. They may be used as bases for impregnating materials, or as tapes or for direct insulation without further treatment.

Much the most important fibrous material in use is cotton, and next to it comes silk. Both fibres are organic, and consist of elaborate molecular cells, exhibiting a crystalline structure and embedded in an amorphous, putty-like, basic substance. Between the single elementary fibres are spaces of various sizes acting as capillaries. Since the basic material may swell when brought into contact with any kind of damp, there may be appreciable variations in the cross-section and in the protection given. This absorption of moisture, which continues automatically until a condition of equilibrium between the dampness of the fibre and of its surroundings has been reached, is called the *hygroscopic characteristic*. Electrolytes are always present to some extent in fibrous materials, due to the process of manufacture, and the electrolyte content, particularly with a variable moisture content, has a considerable influence on the conductivity of the fibre and therefore on its insulating capacity. For this reason any kind of fibrous material to be used for insulating purposes should be treated to reduce the electrolyte content to a minimum. The mechanical properties of the fibres are also dependent on its moisture content, and care should therefore be taken when drying not to raise the material too quickly to a high temperature, since then the water leaves the fibre too rapidly and its structure is damaged. The result of this is a marked deterioration in mechanical strength. When drying any fibrous organic insulating material, the temperature should be slowly raised and the final temperature should not be too high.

As stated above, there is always a fixed state of equilibrium between the dampness of the fibre and of its surroundings. Therefore in order to prevent a dry fibre from re-absorbing

water, it should be treated with some form of impregnating material. This subject is discussed in para. 4 below.

In addition to the properties associated with the fibrous structure, all fibrous insulating materials should have two further characteristics. As they are generally exposed to high temperatures in service, they should not be unduly sensitive to heat and should not easily oxidize at high temperatures. These two qualities set the limit for the permissible temperature rise of machines or other apparatus.

The type of cotton usual for insulation consists principally

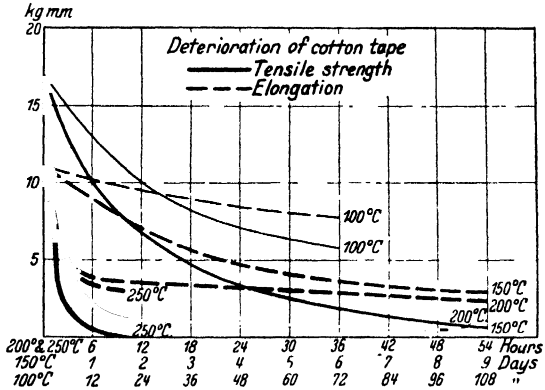


FIG. 209. BEHAVIOUR OF UNIMPREGNATED COTTON TAPE WITH CONTINUOUS HEATING

The solid lines show the decrease in tensile strength and the dotted lines the elongation.

of cellulose. All insulating materials which contain cellulose, whether in the form of cloth or paper, are approximately equal in their capacity for withstanding heat. When the fibre is dried there is a general decrease in its mechanical strength and eventually, with continual exposure to heat, it deteriorates into powder. It is often stated that fibrous material should be as tough as possible when a machine is new, so as to allow for deterioration during service.

The mechanical strength alone, however, is no criterion of the reliability of an insulation, but consideration should also be given to its ability to stretch without actually breaking. For example, it may happen that paper-insulated wires have to be subsequently bent and wound. It has often been shown that papers with very little tendency to tear have completely

failed in service after this additional handling because their capacity to stretch without cracking was too small. It is therefore advisable to regard with discretion statements concerning the heat-resisting capacity of woven material and paper, since reliability is only achieved by attention to all the features mentioned. The influence of oxidation on unprotected fibrous material at the working temperatures should also be taken into account. This can be clearly shown by

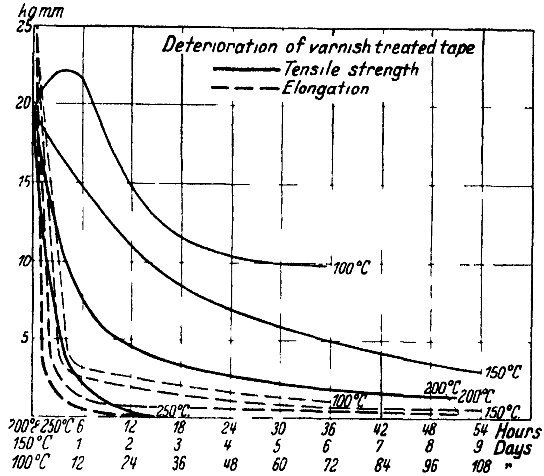


FIG. 210 BEHAVIOUR OF VARNISHED COTTON TAPE WITH CONTINUOUS HEATING

The solid lines show the decrease in tensile strength and the dotted lines the elongation

experiments in vacuum. Fig. 209 shows the behaviour of an unimpregnated cotton tape when exposed to continuous heating at various temperatures. It can be clearly seen that at 100° C. the damage to the fibre is not serious even when the heating continues for a long time, and the fibre remains elastic as shown by the small change in the stretching curve. At 150° C. the influence of heat is much more marked, both mechanical and elastic properties having seriously deteriorated after quite a short time. At 200° C. and 250° C. the fibres deteriorate even more. Other fibrous insulating materials made from cellulose, such as paper and pressboard, behave in the same way. In contrast to this, Fig. 210 shows the behaviour of a varnished tape, that is, impregnated cellulose. It does not tear easily

even after a long exposure to heat at 100° C. On the other hand the elasticity deteriorates after quite a short exposure to heat, and reaches very low values. Insulation in which elasticity is required should not be made from such material.

In this connection it should be noted that no hard and fast rules can be laid down. The operating conditions and the basic material used should always be taken into account when judging insulation. If it is to withstand heating, the impregnating material as well as the foundation of paper or cloth should be suitable for the high temperatures.

Fibrous material should not be treated with any impregnating material which disintegrates under continuous heating and so damages the fibres. Such materials may be added in spinning, in the form of size, or in paper manufacture for fixing and similar purposes. The mechanical strength may show serious deterioration in the presence of such fillers. If it is still possible after the damage has been done, an examination should be made to determine whether injurious materials were contained in the insulation when applied. Certain variations in volume may occur as a result of the hygroscopic properties, and in an unimpregnated fibrous material these variations may be very marked. The result is that when the machine is at rest in a very damp atmosphere the insulation may swell very considerably, and later in operation contract. These continual movements may in some conditions rub through the insulation or push it up together, for example, in slots. Unimpregnated slot wedges behave in this way and according to the material (wood, presspaper, transformer-board, etc.) the changes in volume vary considerably. Impregnation is thus also advisable for the materials used for wedges.

In addition to the deterioration due to continual heating of layered insulating materials, the deterioration in the bonding material connecting the several layers of fibre has also to be considered. The behaviour of hard paper products (sheets or tubes) must be specially mentioned in this connection. To make these, synthetic resin is used which has the property of hardening at high temperatures, or of being converted into insoluble, non-melting resin. This process results in the formation of reaction products, including water, which are generally in gaseous form. When the gases reach sufficient pressure they damage the material and cause blisters. Unfortunately, bakelite products often exhibit a marked tendency to form such

blisters, particularly after boiling in oil. This can only be prevented by very slow increase in temperature during manufacture so that the reaction products can diffuse out of the sheets or tubes. Care should also be taken, when working

(a)

(b)

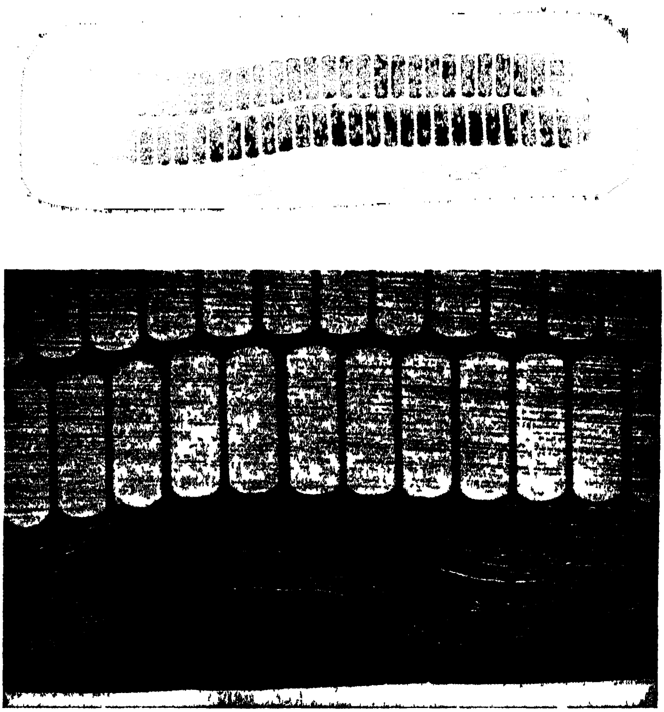


FIG. 211 AIR POCKET IN THE MICA INSULATION OF A COPPER CONDUCTOR, DUE TO UNEQUAL HEATING

(a) Position of the pocket in the insulation
(b) Enlarged view of pocket

bakelized paper products, to ensure that the heating is not too considerable or the temperature too high.

When insulating conductors with mica paper having a natural resin (shellac) as a bonding medium, phenomena may occur like those shown in Fig. 211 (*a*) and (*b*). Due to uneven heating in manufacture, the lower side of the insulation has formed a blister which can be seen even more clearly in Fig. 211 (*b*). When such places reach a higher operating temperature,

they blister still more, and finally cause fissures in the insulation. In the case of insulating materials in layers, certain bonding media will not combine with the basic insulation or the varnish it carries. For example, it is not successful to bond mica with artificial resin containing formaldehyde. Not only should fibrous material be combined with the proper impregnating medium, but care should also be taken to use good bonding agents which raise the heat-resisting capacity of the whole insulation.

Another construction material owing its most important properties to its fibrous structure is wood, which like cotton and paper consists of cellulose. There are three types of cellulose exhibiting different degrees of resistance to external influences such as heat, oxidation, etc., and no general statement of their properties can be made. It is always necessary to consider the ratio in which the three forms of cellulose occur in the object under consideration. Woods are always impregnated, like the fibrous materials mentioned above, in order to fill up their capillary spaces and pith channels, and so reduce their hygroscopic properties as far as possible. For this purpose the impregnating materials which have already been mentioned are used. It should be emphasized that the impregnating medium must be suitable for the wood to which it is to be applied. For example, certain woods, on account of their content of unstable cellulose, can damage the impregnating medium (see para. 5 below). The impregnating medium itself, due to a certain characteristic deterioration, may also exert an effect on the cellulose of the wood and seriously damage its mechanical strength. The same remarks apply to hard paper as well as wood when impregnated with synthetic resin. If the impregnating material reacts further at higher temperatures and gives off gases, the fibre structure may be damaged.

If progress is to be made in the development and application of fibrous material for insulating purposes, further attention to the points stressed here is necessary. No general rules for the properties and strength of insulating materials can be based on a few isolated facts.

2. Sealing and Impregnating Compounds. Fibrous materials such as cotton and paper may be protected against damp and heat by impregnation. A coating of insulating varnish also will often give satisfactory results. There is a difference between

the two kinds of treatment. In the former, individual fibres are filled with the impregnating medium, the air present is driven out and the fibre embedded in varnish. In the second method, however, the spaces between the fibres are not filled up.

Sealing and impregnating compounds are generally not single materials but mixtures of asphalt with resin, of asphalts with oils, or of resins with mineral oils. The composition of the filler may be altered to give the desired consistency. Since a certain plasticity is required, there are limits to the quantity of asphalt that can be added. Only natural asphalts should be used for good insulation, and not tar-pitch which is sometimes incorrectly described as asphalt. It always contains free carbon which has a bad effect from the electrical point of view, although it is quite possible by suitable treatment to remove the carbon from the pitch and obtain a more or less usable product. Vaseline or paraffin can be used instead of the oils mentioned above. When making insulation fillers, the different components should always be well melted through, otherwise on cooling the whole mass separates into individual layers which under some conditions exhibit unequal stresses, which is a disadvantage both electrically and mechanically. It is possible, however, for exclusions to occur without appreciably lowering the quality of the insulating material, and occasionally finely crystallized exclusions are seen in fillers containing colophonium which are formed of abietic acid, the principal constituent of this resin. From the electrical point of view, this has no disadvantages. The exclusion can be brought back into solution by reheating and slow cooling.

It is also possible for insulating fillers to behave satisfactorily during melting and cooling, and only show signs of exclusions after a period in service. Care should be taken to ensure that by systematic testing of the individual components the homogeneous solution retains its constitution permanently.

Further troubles may arise in connection with fillers due to the temperature variations which occur in service. As the temperature rises the filler expands to a greater or less degree according to its composition. In this case also, only tests can show whether the single components are liable to excessive volume changes. This trouble may occur unexpectedly in such apparatus as bushing insulators when the heating is on one side only. The heated side increases in volume and there is a rise in pressure. Since there is no corresponding pressure

on the other side of the bushing, a fracture occurs. It has also been shown in such cases that some mixtures satisfy the general conditions mentioned above, but fail under unequal pressures. It is clear from the above facts that great care should be exercised in choosing impregnations, and that their composition should always be suitable for the purpose for which they are intended. A compound which is suitable for sealing cable ends is not necessarily ideal for filling insulator bushings.

Just as the expansion of the components with a rise in temperature is important, so is the contraction on cooling. The latter is generally known as the *atrophy* of the filler. It is clear that only a series of experiments will determine the most suitable mixtures as regards atrophy. Great attention should be given to this feature as it is the cause of cracks in compound.

The possibility of oxidation when applying the compound should also be mentioned here. This happens when oxidation products which are very viscous and have a low degree of penetration form at the manufacturing temperature. As long as the filler is fluid, the amount of degeneration cannot be determined, but as soon as solidification starts it is apparent that fine films are excluded which do not enter the material to be impregnated but remain upon the surface so that impregnation is prevented. According to the type of the different components, the whole filler exhibits different degrees of sensitivity to oxygen, and care should be taken to ensure that suitable constituents are chosen.

3. Cement. Certain insulators have often to be connected by cement to their supporting or driving members. Like solders, these are applied in liquid form to the place to be cemented, and make a firm joint either by solidifying or by losing their solvent from evaporation. Chemical reactions take place in addition to pure physical changes and thus give the tight joints obtained. A good cement should have both sufficient internal strength and "grip." When the grip is insufficient the cement separates from the parts to be connected as soon as there is any mechanical stress. The strength of the joint, however, is dependent on yet a third factor, the material to be cemented. A metal requires a different kind of grip from that suitable for porcelain or bakelite or similar materials. Cement, like other materials, has no universal type which can be successfully applied in all cases.

The cemented place should be able to withstand other influences besides mechanical stresses. In certain cases, the cement must be free from any tendency to porosity, for example, when the cemented place is to be oil-tight and not liable to deterioration from the oil. In other cases, the cement should not expand after hardening nor be damaged by atmospheric influences. Certain cement mixtures may shrink very considerably during solidifying so that cracks occur. Mixtures are also known which cause pressure either during cementing or afterwards and result in large variations in volume, so that individual parts burst.

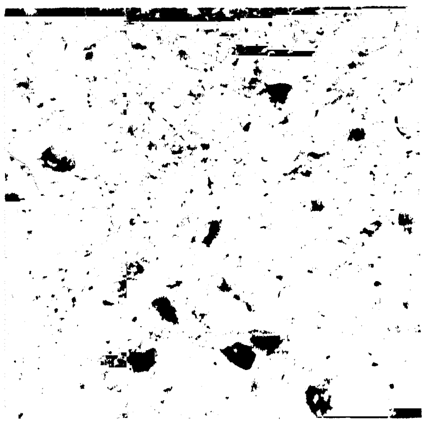


FIG. 212. STRUCTURE OF A LITHARGE-GLYCERINE CEMENT, MADE FROM A LITHARGE OF AVERAGE COARSENESS

Until recently cement mixtures were made empirically, but lately tests have been carried out to show how the different properties of these mixtures can be influenced. The experiments have also shown the great difference in cements. not only as regards mechanical strength, but also in their resistance to chemical, atmospheric and other influences.

Litharge and glycerine cement is very popular to-day. The binding power of this cement results from the chemical action between the lead oxide and the glycerine. According to the kind of lead oxide, that is, how it is manufactured, and how fine it is, more or less glycerine should be added to vary the strength or solidity of the cement. In Figs. 212 and 213 are shown two photographs of the structure of such different

cements. Fig. 212 shows clearly grains of different degrees of coarseness in a hard basic mass. This cement was made from a litharge of average fineness and is very strong mechanically. If the same mixture is used but with a fine red lead oxide, the structure is as shown in Fig. 213. Many small particles can be seen and the basic mass is quite finely crystallized or powdered. The mechanical strength of this cement is very poor. If failures are to be avoided, the fresh consignment of red lead oxide should be tested to determine the mixture which will give the

FIG. 213. STRUCTURE OF A LITHARGE-GLYCERINE CEMENT, MADE FROM A FINE-GRAINED LITHARGE

maximum strength and solidity. It is essential that the lead oxide should be as far as possible free from impurities. Due to long storing lead carbonate, which does not combine with the glycerine, may be formed by the carbonic acid of the atmosphere. When such substances occur in a joint, its mechanical strength generally falls below the permissible limits. The glycerine also should have certain properties. It should have a certain concentration but not be too concentrated. An 85 per cent solution has been found very satisfactory. In addition, it should not contain sulphuric acid or sulphates, since these will form further salts with the lead oxide and seriously affect the strength of the joint. If the mixture of lead oxide and glycerine is properly made and attention paid to the points mentioned, the joint will be mechanically sound and able to resist external influences after it has solidified.

When the mixture is wrong, the joint may be sound but the mechanical strength insufficient and the whole mass porous. Weak places may then occur on the surface due to the carbonic acid of the air, and a joint of this kind is obviously not water-tight.

Cements of magnesium and zinc oxychloride have been used for certain purposes. The same remarks about the fineness of the grain and the manufacture of the oxide also apply to these cements. It also makes a great difference if freshly burnt magnesium or zinc oxide is used, or if it has been exposed to the air for a long time. Even with satisfactory materials and proper mixing, this kind of cement is not so strong mechanically as a lead oxide joint. This is probably because water may be formed under some conditions during cementing, and the process may continue for some time after the joint is apparently complete. There is no important difference in practice between magnesium oxychloride and zinc oxychloride cement. Very good oil-tight and mechanically sound cements have been obtained recently by replacing the magnesium chloride with magnesium sulphate and adding aluminium silicate, giving a cement of the magnesia type.

Still other types of cement are occasionally used but they are only successful in particular cases. Some mixtures will never give more than moderate results.

In addition to cements of this kind which are recommended and generally used for fixing porcelain insulator bushings, steel flanges, and similar parts, other cements are used where less heavy mechanical demands arise, for example, for fixing conductors. Such connections are most simply done with resins, shellac, synthetic resins, and the like. In joints of this kind, there is generally no chemical reaction taking place, but the joining is due to the evaporation of the solvent and to the formation of a sticky resinous layer between the parts to be joined. Joints of this kind are only practicable in thin layers. When applied in thick layers, they generally have a filler added to them, such as powdered asbestos. Such mixtures can also be used with resins and fillers in a liquid condition. When using synthetic resin or shellac, the hardening can be facilitated by applying heat while it is taking place. The cement can also be reheated after it has set, to give additional hardening and make the joint appreciably stronger.

It was mentioned initially that the single components of

a cement may vary very considerably; consequently only general comments can be made here.

4. Insulating Varnishes. All fibrous materials used for the insulation of electrical machines and apparatus are in their unimpregnated state more or less hygroscopic, as mentioned in para. 1, above.

Much the best material for impregnating purposes is insulating varnish. A distinction should be made between impregnating varnish which penetrates into the fibrous material and external varnish which forms a coat over it. There is no "universal" insulating varnish and the composition should always be varied to suit the conditions.

Insulating varnishes can be divided further into varnishes which become dry solely from the evaporation of the solvent, and those in which chemical processes take place and cause a film to form in addition to the evaporation of the solvent. The first group includes spraying varnish, that is, synthetic resin or shellac dissolved in spirit. The second group includes oil varnishes in which the body of the varnish is a mixture of resins or asphalts compounded together with an oil, such as linseed oil or wood oil, which is intended to dry after application.

The drying process makes a further distinction into two classes—air-dried and oven-dried varnishes. The first kind is dried at average room temperature by the air, the second at a higher temperature in a special oven. The different properties of the finished varnish, whether for impregnating or painting, naturally depend on the composition and the method of drying employed.

Insulation varnish naturally needs various properties according to how it is to be used. For satisfactory impregnation it should be easily absorbed by the fibrous material, and should completely fill the capillary spaces. To satisfy the first requirement the varnish should not be too viscous and at the same time should not separate on being absorbed, since otherwise all the solvent will be taken up by the fibres while the varnish is left on their outer surfaces. When the solvent evaporates on subsequent drying it will burst the surface of the varnish and cause hair cracks. For the second requirement the varnish should have a certain consistency even though it has to be absorbed by the capillaries. This, however, is usually achieved in practice by using a solvent which evaporates after application. These two opposed requirements make it clear that there

is no universally applicable varnish for impregnation. A thin fluid varnish is to be preferred, applied so that in the first stage it is absorbed by the fibres, and in the next stage fills the capillary spaces between them. The first layer of varnish should be thoroughly dry before applying the second, since otherwise the second impregnation will damage the first. For this purpose, oven dried oil varnishes are most suitable. Fibrous insulating material treated in this way can have an additional surface coating applied, and for this an air drying varnish is best, applied either by spraying or dipping. Low pressure spraying pistols have recently been used for this purpose and are more suitable than the former high pressure pistols, which sprayed the varnish too violently.

Air-drying varnishes include not only solutions of resins or asphalts in spirits or other solvents but also varnishes in which the varnish body contains a drying oil. Spirit varnishes generally have the disadvantage that they form a more or less brittle film, which under certain operating conditions is liable to develop hair cracks in which damp or dirt can accumulate. The best air-drying varnishes are those which give a more elastic film. Although the spraying of insulated parts with air-drying varnish has a certain advantage, it needs to be done with care, otherwise certain parts will have an uneven coating, or perhaps there may even be places not entirely covered. This is not so likely to happen with dipping.

Insulated parts impregnated with varnish and having to operate under oil—for example, the windings of transformers—should not be liable to damage from the warm oil, so that for this purpose only special varnishes are suitable. If it is not sufficiently dried through, or is not entirely suitable, the warm oil tends to dissolve the varnish from the fibrous material, and serious deterioration may be caused in the oil from certain varnishes. Insulations of this kind should be very carefully selected.

When repairing varnished machine parts it should be remembered that air-drying oil varnishes will not generally resist varnish solvents, and when the new liquid varnish is applied, the solvent may cause the original varnish coat to swell or soften, or may even dissolve it entirely. When the parts are redried in an oven the new coat of varnish, as a result of the swelling of the old coat, may not hold properly or may have an unsightly appearance. In these cases the drying

should be very carefully carried out. It is advisable whenever possible to impregnate the repaired parts before assembly, to dry them and then assemble them in the machine, finally giving a further coat of varnish. In these cases spraying is to be preferred to dipping, since with the spraying pistol it is much easier to deal with the individual parts than with dipping.

With any kind of varnish treatment great care should be taken to avoid bubbles, since the varnish does not dry through in the thick layers, and when it becomes heated the bubbles are driven out. Rotating parts are best impregnated while in rotation, since the superfluous varnish is then thrown off. With large machines or parts which have to be laid on one side for drying, care should be taken that they are as far as possible turned over to avoid any accumulation of the varnish which would give an uneven appearance.

When choosing insulating varnish, the method of application and its purpose should be considered, and also the conditions in which the finished machine or apparatus will work. In this respect also there is no universally applicable varnish which will satisfy all requirements. For example, a varnish which is to be proof against damp is quite different in composition from one to withstand heat. Varnish coats exposed to acid fumes need to be quite different from those liable to be attacked by alkalis. The windings of machines may in different situations have either liquid or solid matter collecting upon them, for instance, oil thrown from the lubricating system. Air-drying varnishes containing oil are generally sufficiently proof against lubricating oil at room temperatures even when they will not withstand warm mineral oil.

The surface may also become covered with dust or other matter, and in such cases the winding should be cleaned periodically. This is best done with compressed air, which should be dry and free from oil, but brushes and cloths may also be used. If the layer of dirt is stuck fast to the winding by oil or other material, it should be removed with some solvent. Benzine is usually quite suitable, preferably light benzine. Care should, of course, be taken to see that the air-dried oil varnish is not soluble in benzine, and also that the final varnish coat is not seriously attacked by it. When this happens it is advisable, after thoroughly drying the machine to spray it again with varnish. Sometimes alcohol can be used as a cleaning medium, but soda-water should always be

avoided since it is likely to attack the layers beneath the dirty outer coating. Benzole is another solvent which is not invariably suitable. It cannot be used where the windings have a final coat of air-dried asphalt varnish, since asphalts are nearly all soluble in benzole.

5. Insulating Oils. Mineral oils are generally used to-day in switches and transformers. These consist of mixtures of hydrocarbons, which according to their derivation can be made up variously and so exhibit different properties. Suitable distillation and refining of the natural oils produces the highly specialized insulating oils. These should be manufactured with the greatest care, not only in order to satisfy the working conditions, but so that the transformer shall not become a source of danger. All mineral oils have only a limited resistance to heat, and to oxidation from atmospheric oxygen.

The insulating oil is constantly exposed to these two influences in transformer service, and it should be thoroughly tested to ensure that it is sufficiently stable. Oxidation products tend to form in it, due to atmospheric oxygen and the high temperature. The most objectionable of these are black sludgy deposits. This sludge formation is not, however, the cause of the trouble but the result.

(*a*) Sludge Formation. When oxidation occurs, acids soluble in oil are first formed which are determined by the *acid content test* (number of milligrams of potassium hydroxide required for neutralization per gramme of oil). There is a general idea that these acids are particularly dangerous and likely to damage the coil insulation, but it is more accurate to say that the acid content cannot exceed a certain fixed amount without damage to the transformer. It should, however, be remembered that this test only shows the quantity and not the kind of acid present. When the insulating oil deteriorates, various acids form according to the nature of the oil, which are another quite different source of danger to the windings. The acid content does not provide any information concerning this, and the oil should certainly not be renewed solely on account of its acid content. As deterioration proceeds, these acid reaction products give rise to polymerization products which are not soluble in oil at high temperatures, and at ordinary temperatures are freely deposited as sludge. Acids are present in these substances also, but as long as the transformer is operating at a high temperature,

they are not dangerous. With oil coolers, however, the temperature decrease is so considerable that the sludge in solution may be deposited on the cooler tubes. Since these decomposition products are poor conductors of heat, the heat transfer is affected and the oil is no longer properly cooled. Due to the raised temperature, further decomposition goes on and the products which are not soluble in warm transformer oil are deposited on the windings in the form of asphalt-like matter. This also occurs in the oil cooler, since the sludge which was formerly soluble when deposited on the cooler tubes is transformed by continuous heating into insoluble asphalt-like material. This process may so encrust the cooler as to put it completely out of action, and if it is not noticed in time the consequences may be serious. If the deposits on the cooler tubes are not too old, that is, if they have not been too long exposed to heat from the warm oil, it is still possible to clean the cooling systems with benzole, since the first decomposition products are soluble in benzole. If, however, asphalt sludge has already begun to form and it has been exposed to heat for some time, the incrustations are usually so hard that they can no longer be removed by this method. In this case, chloroform should be used as a solvent instead of benzole but in bad cases even this may not be successful. The only remaining expedient is to clean the tubes by mechanical means.

In transformers the products of deterioration may in the same way settle on the windings, cross-pieces and other parts, as shown in Fig. 214. Due to the poor heat-conducting capacity of the sludge the windings may be excessively heated and deterioration is accelerated. The raised temperature may even result in damage to the cotton, if the transfer of the heat losses is insufficient. This, however, is not so much a direct effect of the transformer oil as damage caused by heating arising from the deposits. The same solvents for the sludge as are used on oil coolers are suitable for transformers. Great care should be taken to ensure that after the sludge has been removed, the solvent is also thoroughly cleaned out from the windings before the transformer is put back into service.

In addition to the above products of decomposition, substances are produced in the oil which are not stable, and shortly after being formed break down again and set free oxygen, which may be very active and attack the cotton and other insulating material. There are certain oils with a particular

tendency to form such unstable products and these are much more unsuitable than oils with a high acid content. With these reactions little or no acid is formed, so that the acid

FIG. 214. TRANSFORMER WITH WINDINGS AND CONNECTIONS CHOKED WITH ASPHALT-LIKE PRODUCTS OF DETERIORATION, DUE TO THE USE OF UNSUITABLE OIL OVER SEVERAL YEARS

content test gives no indication that the process is taking place. As a rule very little sludge is deposited in connection with it, so that a very inferior oil may show no signs of sludge or discoloration.

The various types of deterioration of mineral oils are very largely dependent on the degree of refining, that is, how and to what extent the oil is treated in the refinery to remove resinous substances. It is thus not so much the original constitution of the oil as the treatment applied to it which determines its behaviour in service. The original source of oils will be discussed later.

(*b*) THE SAPONIFICATION FACTOR. To determine certain reaction products the *saponification factor* has recently been introduced. This gives the amount of material which can be saponified in 1 gramme of oil. It should be noted that here again no information is given as to the kind of reaction product, only the quantity. As stated before, some of the most dangerous decomposition products cannot be detected by ordinary analytical methods. The same applies to the saponification factor. With its help, well-defined reaction products soluble in oil can be detected which, however, can occur in quite large quantities without causing any damage at all. On the other hand, oil with a low saponification factor may be very inferior. Just as it is impossible to determine from the acid content test if the transformer oil should be renewed, so it is useless to use the saponification factor for this purpose. In the interests of rational oil economy, one should avoid attempting to estimate the age and probable future service of the oil from such analytical numbers, since these are concerned entirely with quantity and give no indication as to the kind and behaviour of the oxidation products.

It is obvious that electrical overloading, leading to increased heat losses, accelerates deterioration. In general, it can be said that up to the average temperatures of 55° C. to 60° C. these processes take place comparatively slowly. If the temperature is raised up to 90° C.–95° C. the deterioration shows a marked acceleration. At even higher temperatures, 115° C.–120° C., another form of deterioration starts and volatile products are formed which are very damaging to the insulation. Besides the temperature, the presence of metals accelerates deterioration more or less rapidly. Much of the most active metal in this respect, which comes into contact with oil in the transformer, is copper. The other metals, such as iron, zinc, or light metal are almost inactive. The influence of copper, however, is generally very much overrated since it only accelerates deterioration at high temperatures.

It is occasionally stated that insulating materials introduced into the oil with the transformer may have a bad effect on the oil. Unsuitable woods may actually have a very bad effect and this applies to the wood used for the construction of the transformer. It is particularly important to ensure that the wood is previously treated so that as far as possible it is free from resin, since this is likely to cause deterioration. Even woods from which the resin has been removed may have a bad effect on the oil due to their chemical composition.

Care should be taken that the wood parts are joined with suitable glue or cement. Cold glue which contains alkalis must not be used to increase the strength of joint. The additional matter in insulating woods may be very damaging since it is frequently hygroscopic and may form creepage tracks, so that the oil at these places is seriously decomposed and provides a starting point for the general deterioration of the oil.

Of the remaining fibrous materials used in transformers, pressboard and similar products may be mentioned, which sometimes have an effect on the oil, although only slight, perhaps due to unsuitable manufacture. In this case also, the chief aim is to use suitable adhesives. For instance, badly washed acid dextrine may be used to glue pressboard, in which case similar phenomena occur as with wood.

For impregnating windings, insulating varnishes are generally used, consisting partly of resins and partly of asphalts mixed together with drying oils. If the composition is not right, or the drying process is not continued for long enough, these varnishes are more or less soluble in hot mineral oil. The dissolving of the varnish naturally makes the impregnation ineffective, and the constituents of the varnish may have a bad effect in solution in the hot oil, if they are of certain chemical composition. Neither of these troubles is likely to arise if the right type of varnish is used, and adequate impregnation and drying applied. In this case no abnormal deterioration of the transformer oil takes place.

(*c*) Specification and Testing of Oil. What, then, are the requirements which should be fulfilled by a good mineral oil free from deterioration even in the event of overloading? Some time ago, the most incredible specifications were issued on this subject which, however, did not establish the presence of unsuitable constituents and were therefore not suitable for ascertaining good oil. They merely had the effect of

confusing the oil manufacturers without having any technical value.

Obviously one cannot discuss here the different methods of testing oil, but we shall mention a few of the important controversial points and their significance from the technical aspect.

The specific gravity of transformer oil is generally set out in specifications in order to ensure the continuity of the supply. It should, however, never be considered as a quality on which to judge the oil.

The flash-point should always nowadays be determined in an open crucible. Its results have only a relative value and cannot be used as a criterion of the suitability of an oil. For example, in service the flash-point drops as the oil deteriorates. It only shows the temperature at which the gases given off will be ignited by a flame without the oil itself burning. It is not any indication of the danger of burning. When, however, there occur in service any large or small steady arcs, many easily ignited decomposition products are formed, and the flash-point no longer has any significance. It should therefore only be used as mentioned above and not taken as any indication of quality.

In transformer oil, the viscosity is one of the most important features. In order that the heat losses shall be conducted away as efficiently as possible, the oil should have a certain fluidity. Since the operating temperature generally reaches a value which reduces the viscosity appreciably, this condition is usually fulfilled. It is, however, much more important to know how the oil behaves at low temperatures, since when transformers are in open air situations under some conditions, very marked thickening of the oil may occur due to its excessive viscosity.

In this connection it has been established that one should distinguish between paraffins and naphthenes. The first have the unfortunate property that according to the method of treatment in the range 0 to — 5° C. they become very viscid due to the exclusion of paraffin, or may become of the consistency of vaseline. It is even possible in cooling radiators for paraffin to separate on to the cold walls, and the cross-section of flow is appreciably reduced or even completely closed up. Naphthene oils have not this characteristic and they are fluid at very low temperatures (— 30° to — 40° C.) without any exclusion. For open air stations only these oils are permissible.

It has often been stated that Russian oils make the best transformer oils: actually the source of the oil is of much less importance than its chemical composition and the treatment it receives. No attempt will be made here to discuss the differences in Russian, American and other oils.

As mentioned at the beginning of this section. transformer oils should have a certain ability to withstand heat and oxidation. The methods which are recommended for testing this are divided into several categories. The principal rule is that determination of a single reaction product, such as acid content or sludge, is not sufficient. In the case of oxidation we have also seen that reaction products occur, which have a bad effect on the fibrous material, but cannot be detected by the usual analytical methods. The testing temperature, that is with artificial deterioration, should not exceed 115° C. since the groups of deterioration products above and below this line are quite different. If metals are used for accelerating the decomposition, it should be noted that copper, zinc, tin, and aluminium cause the same course of reaction, but copper is the most active. Metals such as lead cause quite a different decomposition process and the results of these different tests cannot be compared, nor can the suitability of the transformer oil be based on such comparisons. The dangerous unstable reaction products can only be detected by their damaging effect and not from analysis.

In addition to the properties mentioned, there are a few other characteristics of transformer oil to consider. For instance, all ordinary mineral oils are more or less hygroscopic, and those which are particularly bad in this respect should not be selected. The oils should not contain impurities, such as fibres or dust, which increase the hygroscopic property. When mineral oils decompose, water is sometimes one of the products, and if such hygroscopic material is already in the oil, the effect may be bad. The electrical resistance particularly is lowered by such impurities. The oil should be dried and purified by suitable processes to keep it fit for service, and these processes are generally combined.

The drying is generally done by heating the oil to a fixed temperature in a vacuum. Care should be taken that at the beginning the temperature is very slowly raised, so that air dissolved in the oil does not act as an oxidizing agent and start deterioration. Small amounts of oxidation, however, may

constantly be caused by the atmospheric oxygen contained in the oil which, however, does not have any effect at all on the quality of the oil and its behaviour subsequently in service. If any tubes or flanges of the drying apparatus are not tight, air may be sucked into the oil so that it may be oxidized to a very considerable extent even during drying. This is not likely to have any serious effect when oils of good quality are employed. Care should be taken when drying, to remove not only the damp, but also the dissolved oxygen from the oil.

(*d*) Cleaning of Oil. For cleaning insulating oils, different processes are used. The oldest and most popular method is by means of a filter press, which removes all impurities, such as particles of sludge, with filter paper. It is often stated that this process allows fibres from the filter paper to get into the oil. If water is also to be removed from the oil by filter paper, the paper should be highly absorbent. Such filter paper may easily be torn, but this difficulty may be overcome by using two or three layers, or specially toughened paper which holds back even the finest fibres. For the drying to be successful, the paper itself should be thoroughly dried before use.

For some time separators of various designs have been used for cleaning oil. It is quite practicable to remove large impurities from the oil with this apparatus, but finely distributed water cannot be removed in this way. On the contrary, it is more likely to be finely emulsified by being shaken. If the oil is tested for electrical resistance immediately after separating, the value of resistance will be high, but after standing for a time the fine particles of water separate out again and appreciably lower the resistance. A further disadvantage is that separating generally has to be done at high temperatures so that the whole of the sludge goes into solution and only separates out again when the oil is cold. If fresh oil is cleaned in this way there is the danger with certain systems that the oil, by being reduced to a spray, becomes saturated with air and due to the high temperature becomes oxidized. This process is not recommended since, after freeing the transformer, oil pipes, etc., carefully from air, an apparatus is connected to it which distributes air, and therefore oxygen, finely again through the whole system. On this account modern separators work in a vacuum or in an inert gas which removes this last disadvantage. The other disadvantages arising from cleaning the used oil still remain.

Recently other cleaning processes have been recommended which to some extent have proved successful; for example, ultra-filtration, electro-capillary cleaning and stream line filter presses, which are manufactured by the Stream Line Filter Co. in England.

Mineral oils are also used in oil switches as a dielectric. To simplify the stocking of material, the same types are used for this purpose as for transformers. In this case, the resistance to oxidation does not play so great a part as for transformers. For an oil to be satisfactory the same qualities are required as those mentioned briefly above. It should be noted that for open-air plant the solidification temperature should be as low as possible, so that on switching, in cold winters, the oil retains sufficient fluidity to flow and extinguish the arc as rapidly as possible. For this purpose also, naphthene oils are more suitable than paraffin oils. The specific gravity should be lower at low temperatures than that of water or ice, so that these do not rise in the oil or remain suspended in it, or they may cause small flash-overs between the switch-contacts and the switch casing. Unfortunately in practice too little attention is usually paid to this point.

During switching the mineral oils are decomposed with the formation of gaseous products, mainly hydrogen and coal gases. According to the switching process various substances are deposited, either coarsely flaked or finely divided. When cleaning with a filter press, these can be removed from the oil, but with the separator they are merely more finely distributed in the oil and form permanent decomposition products which are practically impossible to remove.

(*e*) Wood Oils. Formerly wood oils were used in transformers instead of mineral oils. These are obtained from the dry distillation of resin, and after suitable refining were sold in various degrees of fluidity. At the higher temperatures which occur in service they do not produce the same decomposition products as mineral oils, but form practically non-fluid, asphalt like polymerization products, which settle down as sludge until the whole mass is equally thick. In Fig. 215 a transformer is shown from which the thickened resin oil could only be removed after several hours heating. In order to reduce the time somewhat, the resin oil was thinned from time to time with oil.

Resinous oils must not be used in oil switches since they give

very heavy carbon deposits due to the decomposition caused by the arc. Small quantities of wood oil have a very bad effect when added to mineral oils. There is a rapid formation of heavy sludge due to the forced oxidation of the mineral oil by the wood oil residue. Care should be taken to avoid such mixtures.

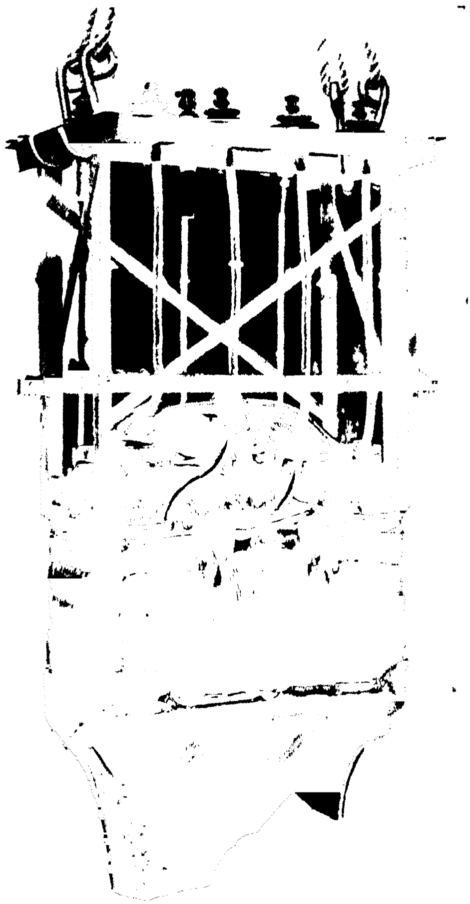


FIG 215 TRANSFORMER FILLED WITH RESIN OIL

The oil has been reduced to an asphalt-like consistency by continual heating.

While vegetable oils and mineral oils may definitely not be mixed, there is always a doubt as to whether two mineral oils will mix without causing any trouble in service. We have already mentioned that the descriptions "American" or "Russian" are practically meaningless in view of the high standard of refining usual to-day, and are no criterion at all of the quality of the oil. When it is desired to mix mineral oils, it must be known with certainty whether they belong to the naphthene or paraffin class. If the kind of oil is known it can be stated that oils can be mixed, if they are chemically similar and have, by suitable refining, come to have the same values for their various characteristics. The actual refining process employed does not play any part in determining

whether the oil will mix or not. Mixtures of this type will be similar to their components as regards their electrical properties and chemical behaviour.

(*f*) Regeneration of Oil. For some time, used oil has been made suitable for further service by the process known as *regeneration*. Complete regeneration is, of course, the same thing as refining. This process removes certain materials such as acids, sludge, etc., from the used oil. Certain other decomposition products are, however, formed in service which are soluble in oil and not detectable by the usual analytical methods. Regeneration will not remove these. Regenerated oils are, as regards dielectric properties, very much inferior to new oils, although the analytical values after the treatment are almost as good as originally.

It is always debatable whether the oil should be cleaned or renewed. To-day the deciding factors are generally the acid factor and the saponification factor; but as already mentioned, these do not give any real indication of whether the oil is suitable for further service. Extensive tests of the dielectric behaviour are necessary for a sound decision. Unfortunately, until recently tests of this characteristic have generally been neglected. The question of renewing the insulating oil cannot usually be solved by fixing permissible values for acid or saponification factor, since it should be determined separately for each case, taking particularly into consideration how much tendency there is for the oil to attack the insulation.

It was mentioned before that the dielectric behaviour of the oil is particularly affected by damp. We can best expand this by saying that the presence of moisture can be most easily determined by the following test. A small sample of oil is heated in a test tube over a Bunsen flame and note taken if any water that is contained in the oil is given off by observing the customary crackling sound. If the result of this test is positive the oil should be thoroughly dried. It is more satisfactory, however, to determine the breakdown capacity which varies appreciably with even the smallest traces of water.

The formation of sludge in glass expansion vessels—on bushings—is mentioned in Chapter XXXI. This, however, does not lower the electrical resistance of the oil but the phenomenon should be regarded as undesirable because it is unsightly. The properties of oil both as regards sludging and breakdown strength are set out in B.S.S. 148, where the recommended test procedure is also described.

CHAPTER XL

INSULATING MATERIALS: ELECTRICAL TROUBLES

1. Breakdowns. When breakdowns occur through solid insulating materials, the internal material is rendered useless as an insulator by a conducting path or an extensive burnt place. Fluid or gaseous insulating material may, however, be renewed at the burnt place by the flowing in of sound insulating material, and thus regain its original insulating capacity.

The cause of electrical puncture is usually excessive voltage, resulting from electrical atmospheric disturbances (direct or indirect striking by lightning). Short circuits and breakdowns to earth as well as faulty switching are also responsible for excessive voltages, but their causes cannot be discussed in detail here.

Another group of causes of electrical breakdowns is the actual failure of the insulating material itself, that is, its technological state, and the alteration of this with heat, damp, mechanical stress or chemical attack, as well as entry of foreign matter which damages the materials.

(*a*) SOLID INSULATING MATERIALS. The processes causing the breakdown of solid insulating material are not even yet completely understood and are still the subject of scientific research. The following fundamental points can, however, be mentioned. Electrical breakdown is very considerably influenced by the heating of the materials and a breakdown can often be traced directly to previous overheating. The question then arises as to the source of this heating. In solid insulating material which is in an alternating electrical field (most high-tension insulations are in practice on a.c. supplies) losses arise known as *dielectric losses*. These are dependent on the magnitude of many factors, including temperature, and in most materials may be such that in service the surroundings also are heated. When the insulating parts are properly designed and carefully manufactured from suitable material, normal voltages should, however, not cause excessive heating, since the small losses only raise the temperature of the parts slightly and the heat is naturally conducted away to the surroundings.

The danger of breakdown due to overheating first arises when the internal or external causes of heating increase excessively. Insulation of unsuitable material or of careless construction may have excessive dielectric losses either generally or in one place only. The increased heating then causes a greater excess temperature so that the losses increase still further. The temperature of the insulation finally reaches values which are critical for the material and dangerous, and a conducting path finally occurs, resulting in a thermal breakdown. The insulating material is therefore damaged over a large area by the overheating, and burnt by the subsequent puncture. The breakdown thus takes place entirely due to causes external to the insulation itself. Fig. 125 shows the effect of a thermal puncture on a bad condenser bushing.

External overheating by adjacent constructional parts also favours thermal breakdowns, in that it raises the ambient temperature and consequently the internal temperature of the insulation. Breakdowns may happen in designs which are heated from external causes to a high temperature, for example, the terminal bushings of transformers, where the under part is heated by the oil, or machine coils where the copper and iron temperature heats the insulation from both without and within beyond the permissible limit.

The effects of the puncture are dependent on the energy which may flow to the place where it occurs, and the effectiveness of the protection; since the puncture generally also means a short circuit, or a breakdown to earth, it should be cut out by the overload protection provided.

Preventive measures against this phenomenon are careful manufacture, voltage testing and eventually loss measurement on the finished product. This is usually constantly carried out by the supply firms. In service the insulating bodies should be protected against unforeseen heating by the surroundings. Heating to a critical point may occasionally be detected by feeling with the hand after repairs. Continual over-voltages may lead sometimes to increased losses and consequent heating, but it is not likely that the voltage increases arising in service will have unfortunate consequences if the insulation is quite sound at the rated voltage.

Punctures which could not have been caused by heating have also been noticed on solid insulating material in addition to typical thermal breakdowns. These "cold" or pure electrical

punctures generally occur as the instantaneous consequence of high over-voltages, either when testing or in service. The dielectric punctured in this way exhibits only a straight line puncture as in Fig. 216, and there are no traces of any previous heating of the area. This type of puncture can only be prevented by proper dimensioning of the dielectric and suitably shaped electrodes. At the same time, an efficient over-voltage protection should be provided to prevent such dangerous stresses.

Several points should be noted when designing solid insulations. The stress an insulation will withstand depends not only on the type of stress but on the variation in any particular material as regards constituents, manufacture, shape or reaction to temperature. It is therefore impossible to give reliable general rules for this. Tables giving the approximate permissible voltage for 1 cm. thickness of various insulating materials should be applied with discretion, and it should be noted that the same material supplied by different manufacturers may exhibit very different electrical characteristics. In addition, rules which often fail to provide an adequate margin of safety cover the kind of voltage (a c. or d.c.), the frequency, shape of electrodes (surfaces, curves, points or edges), and their pressure, as well as rules on previous treatment and the condition of the insulating material in question. Moreover, the voltage which causes the puncture is not as a rule proportional to the thickness of the dielectric, but follows the typical curve shown in Fig. 217.

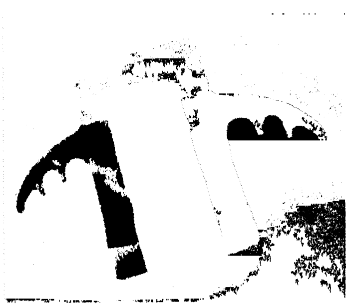


FIG. 216 ELECTRICAL BREAKDOWN THROUGH AN INSULATOR CAP

Reliable information on the dielectric strength of a material can thus only be given by the manufacturer or a reliable testing station. Fig. 217 shows, for example, what information is desirable when using pressboard or transformer-board. The margin of safety can be seen for any degree of stressing of the material.

(*b*) FLUID INSULATING MATERIAL (OILS). The dielectric strength of oil is lowered by any impurities present, as mentioned in Chapter XXXIX, para. 5. There are many and

various impurities to be considered—for example, moisture of various kinds, atmospheric influences, products of deterioration from internal or external sources, foreign matter such as carbon particles, dust or fibres—so that no simple breakdown test of the oil, for instance, with the usual testing apparatus suffices to determine its insulating capacity.

Investigators have advanced widely different explanations to account for breakdowns in technically "cleaned" oil. While moisture in the oil has been stated to be the predominating

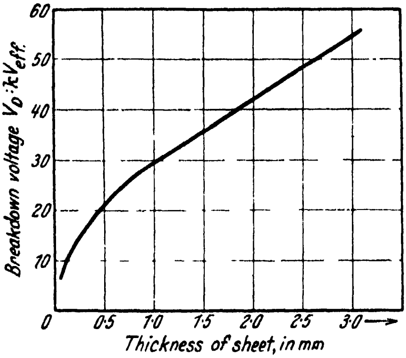


FIG. 217. BREAKDOWN VOLTAGES BETWEEN BALL AND PLATE ELECTRODES FOR TRANSFORMER BOARD, PREVIOUSLY BOILED FOR 36 HOURS IN TRANSFORMER OIL AT 105°

The voltages were applied for one minute under oil.

cause of breakdown, solid impurities such as fibres may cause "bridge-formation" and so lead to electrical breakdown. Actually both influences are present together in the oil and both lower its strength. Chemically pure oils which are entirely free from water and impurities actually show breakdown strengths of over 200 kV. eff. per cm. For practical purposes, oils giving values of 100 kV. eff. per cm. with the usual testing, methods are considered sufficiently good. These values are, of course, only relative and cannot be used as a standard for the oil independently of other factors (see Chapter XXXIX, para. 5).

With solid insulating material a very high field strength or peak at one point immediately damages the material there, but with oil the process is quite different. To produce a dangerous peak effect and cause a subsequent breakdown, it is necessary according to the experiments of Roth for the

electrical voltage drop, for some distance from the point or edge into the oil, to be very high.

Corona discharge phenomena can occur in oil as well as in air and thus bring about chemical action. This is, however, extremely unlikely in service.

(c) AIR. The electrical breakdown of a layer of air between two electrodes (conductor to conductor, or conductor to earth) can be explained as due to the presence of electrically charged particles of gas (ions). If the field is sufficiently strong, these form a conducting path which remains under the voltage of the electrodes. It offers a certain resistance to the arc current which decreases with increasing current strength. The energy available, which is often quite considerable, turns to heat and ignites the whole space which is bridged over between the two electrodes. If there is no suitable arrangement for conducting away the arc or extinguishing it (either arcing horns on isolators or magnetic blowouts on air break switches) and the energy is sufficient, a steady arc is likely to occur. This may melt the electrodes as well as the part of the installation in contact with the arc (conductors, instruments, and constructional parts). "Wandering" or "climbing" of the arc does not necessarily hinder this.

Assuming that the air distance was properly dimensioned in the first instance, the breakdown may have been caused either by an over-voltage between the electrodes or some fault on the electrodes themselves existing at normal voltage. Only properly built and maintained plant equipped with over-voltage conductors is proof against the consequences of over-voltages. (See Chapter XXX, para. 6.) The suitability and effectiveness of the different kinds of over-voltage protective apparatus are still a subject of dispute. Modern switching plant for very high voltages usually has built-in protective devices.

The causes of breakdowns through air are often actually to be found in the electrodes. At different places in this book attention is drawn to the effect of loose terminals or conductor connections. With current surges, these may be so overloaded or stressed that glowing metal is thrown off them and an arc started.

Corona discharges from live surfaces have a similar effect in the air, but not so quickly. Sharp angles and edges are usually the cause. On high-tension installations such places are avoided by suitable shaping of the electrodes. Even on

these, discharges are likely to appear after they have been some time in service, since the surrounding air always contains more or less dust and grains or fibres are deposited on the electrodes which cannot always be removed. The advantages of curved surfaces are then sometimes lost.

In designing insulating distances in air, allowance should be made for this accumulation of dust and the formation of discharge tracks. To be quite safe the distances should be calculated for the electrode shape from point to point. For this the formula below based on experience may be used. This applies from about 40 kV. working voltage upwards.

$$V = 14 + 3{\cdot}2 \times d$$

in which V in kV. = the effective breakdown voltage of the air layer and d in cm. = the necessary electrode distance for the voltage concerned.

For installations situated very far above sea-level, it should be remembered that air resistance to breakdown decreases with a decrease in pressure, and it can be assumed that it is approximately proportional to the average barometer height.

The danger from corona discharges should not be overrated in the open where there is a natural movement of the air, but the first opportunity should be taken to remove the cause of such discharge. It is serious in completely closed spaces, in solid insulation containing gas or air, and fibrous material is particularly susceptible in this respect. In Chapters II, para. 10, and XX, para. 2, two cases of such internal corona discharge are mentioned.

2. Flash-overs. This term refers to discharges between two electrodes along the dividing layer of two insulating materials, for example, along the surface of an insulator in contact with air or along insulating parts under oil, as well as along a separating layer of two different solid insulating materials. The discharge along these boundary surfaces is no longer determined by the electrical strength of the boundary material. More often the process starts as partial conduction on the surfaces.

This current conduction is greatly favoured by deposits of foreign matter from the surrounding air or oil. On surfaces exposed to air there may be a film of damp, dust, soot (on burnt places), or oil, and on surfaces under oil there may be sludge from the oil, soot or even woven fibres. Liquid and solid

deposits together may even lead to the formation of complete covering layers in which creepage tracks easily form and cause flash-overs. The danger of flash-overs is that they often occur very much earlier than the breakdown in the adjacent insulating bodies. The results depend on the energy present and the material concerned. Insulators in air are on this account provided with devices to induce a breakdown across the free

FIG. 218. PORCELAIN INSULATOR SHOWING TRACES OF BURNING DUE TO ARC

air before a flash-over occurs along the surface, a familiar example being the guard rings and horns on high-tension outdoor-type insulators. No insulating material, not even porcelain, can withstand the steady arc resulting from a flash-over. As shown in Fig. 218, it is quite possible for the glazing to be damaged by burning.

Even in solid insulating materials which are constructed in layers, flash-overs are more likely along the dividing layers than across them. This is due to the structural incompleteness of the dividing layers, although foreign matter cannot be deposited in this case. The electrical strength along dividing layers in solid material is often a fraction of the breakdown value at right angles to the grain of the material.

APPENDIX

SOME NOTES ON BRITISH AND CONTINENTAL PRACTICE

THIS book deals with the more common types of trouble which are liable to occur, and forms an effective groundwork for the less frequent and often much more obscure type of failure. It was written in the first case having in mind apparatus made on the Continent, and as readers of this translation will, in many cases, have to deal with British and American products, the following is a brief survey of the differences between the National Standards and the manufacturing practices on the Continent, in Great Britain and America.

Temperature Rise. The most marked differences in practice are probably to be found in the permissible temperature rises, and Table A gives a comparison between the British, German, and American standards for motors.

TABLE A

	British B.S.S. 168/1936		German V.D.E. 0530 1934	American A.S.A. (A.I.E.E.)	
	Ventilated machines	Totally Enclosed Machines		Ventilated Machines	Totally Enclosed Machines
Maximum Ambient Air	40° C.		35° C.	40° C.	
Insulated windings	40° C.	50° C.	60° C.	40° C.	55° C.
Iron in contact with the above . .	40° C.	50° C	60° C.	40° C.	55° C.
Commutators . .	45° C.	55° C.	60° C.	55° C.	65° C.
Sliprings					
(*a*) ventilated .	45° C.	55° C.	60° C.	55° C.	65° C.
(*b*) totally-enclosed .	55° C.	55° C.	60° C.	55° C.	65° C.
Single-layer field windings . .	50° C.	50° C.	70° C.	50° C.	65° C.

Note. All with Class *A* insulation.
British and American rules—temperatures by thermometer.
German rules—temperatures by thermometer, or increase of resistance, whichever is higher.

Ball and Roller Bearings. Ball and roller bearings are used to a much greater extent in Great Britain than either on the Continent or in the U.S.A. They are standardized up to sizes of machines corresponding to 1 000 h.p. at 1 000 r.p.m. in this country, whereas on the Continent there is still a considerable sale for sleeve bearing machines. In the U.S.A., except for small motors, the sleeve bearing still holds the field. The authors have not dealt extensively with the troubles likely to occur with ball and roller bearings, and some notes on these follow. The two main sources of trouble are

(*a*) cage wear;
(*b*) stationary vibration.

The first of these, i.e. cage wear, may arise from a variety of causes, one of the most common being inadequate lubrication. Grease is the usual form of lubrication for this type of bearing, and in service is intended to behave like a sponge containing oil. The grease should exude its oil steadily during the periods between recharging of the housing, and it is this oil which should creep over the cage and races rather than the grease itself, which is some 15 per cent or 20 per cent soap. If the grease releases its oil too slowly, the cage will become starved of lubricant. If the bearing is overcharged with grease, the latter may split up into its separate components of oil and soap due to the churning action, and allow the oil to drain away along the glands. The housings of ball and roller bearings should be packed approximately two-thirds full of the grease recommended by the manufacturer of the machines, and should then operate at least six months without further attention.

Another cause of cage wear may be misalignment of the inner and outer races. If the inner race is canted with respect to the outer, the path of the rollers or balls, as the case may be, is not true and they are forced violently into contact with the cage during part of each revolution. The misalignment may be due to machining errors at the manufacturer's works, but more often it arises from faulty reassembly after cleaning or fitting of replacements. Grit or dirt on the shoulder of the shaft will throw an inner race out of truth. The alignment of races can readily be checked by means of a clock micrometer with the motor or generator fully assembled. The bearing cap should be removed and the clock micrometer located from the side of the outer race with its plunger resting on the side

of the inner race. If the shaft is revolved, the micrometer will then indicate the amount by which the inner race is out of truth. Next the micrometer should be mounted on the shaft

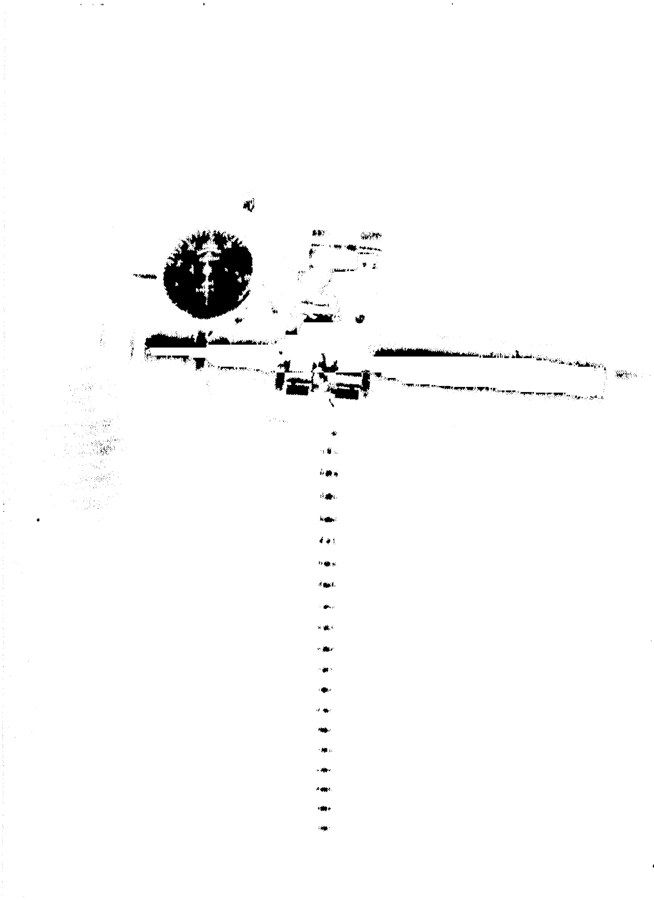


FIG. A. SHOWING THE METHOD OF CHECKING THE ALIGNMENT OF RACES FOR BALL OR ROLLER BEARINGS

(see Fig. A) and the latter revolved, when the misalignment of the outer race will be indicated.

If a motor fitted will ball or roller bearings is subjected to severe vibration while it is not revolving, the rollers or balls

produce indentations in the tracks which, on starting up the machine, cause excessive noise. Naturally, if a motor continues to run in this condition, the surfaces of the bearing races will collapse in due course, but it is interesting to note that bearings with severe indentations from vibration while stationary and making excessive noise have run for long periods

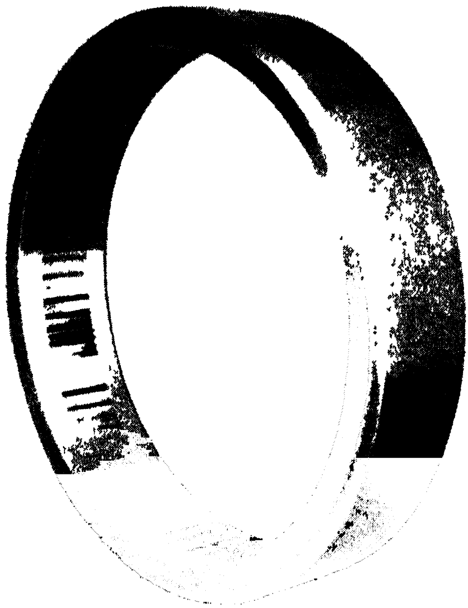


FIG. B. SHOWING THE RESULTS ON A BEARING SUBJECTED TO HEAVY VIBRATION WHILE STATIONARY

without actually failing. A motor of some 300 h.p. operated for five weeks in Africa while spares were coming to hand, and at the end of this period had not actually broken down.

This marking due to vibration frequently takes place during transit to site, and transport for new motors should always be arranged to avoid excessive vibration. Motor lorries with solid tyres are quite unsuitable for transporting machines with ball and roller bearings. Railway wagons should be well sprung. The trouble may also develop in service where the foundations of a motor vibrate severely and the machine is standing idle

for long periods, as is the case with standby plant. It should be noted that the trouble rarely occurs if the machine is revolving, even though excessive vibration is present. Fig. B is a photograph of a typical outer race damaged by vibration while the motor has been standing stationary.

If the marking of the races is not severe, the bearings can be put into work by merely turning the outer race round in its housing so that the marks which are usually at the bottom are lying in some position out of the load area, e.g. at the top. If the inner race is severely marked, this remedy is not effective, but nevertheless, the motor can be run until such time as spares can be fitted. If run, the bearing should be kept under observation and shut down if an excessive temperature rise develops.

Transformers. As in the case of machines, the principal difference between Continental and British transformer practice is in the allowable temperature rises. The limit for oil immersed naturally cooled transformers according to the British Standard rules is 60° C. by increase of winding resistance, whereas the corresponding V.D.E. Rules allow 70° C. rise, also by increase of resistance. The only effect of the more conservative British policy is likely to be elimination of some of the troubles such, for example, as sludging of the oil. This subject is dealt with at length in this book, in the final section on "Materials," and, whether or not the allowable temperatures affect the position, it is certain that in England examples of sludging such as are shown in this book are virtually unknown to-day. In the matter of core building, English transformer practice tends towards the yoke built up from interleaved laminations, rather than the solid machined yoke shown in Fig. 126. This thereby avoids trouble due to pitting of the iron and local circulating currents, but on the other hand, the process of dismantling for any possible winding repairs is much more involved. Transformers have, however, reached a very high standard of reliability to-day, and such troubles as occur tend to be in the auxiliary apparatus such as the cooling systems and tap changing equipment. The Buchholz protective apparatus described in the book is now manufactured in this country, and is undoubtedly an excellent device for limiting the damage when trouble is developing.

Switchgear. In the section of the book dealing with switch and control gear, the fundamental characteristics of contacts

are described and the usual types of troubles associated with them are dealt with. British manufacturing practice in regard to these points is naturally very similar to Continental, and the fundamental differences in switchgear lie rather in the form of protection and the method of extinguishing the arc in circuit breakers. In this country oil-immersed gear is customary, whereas on the Continent, water and air blast circuit-breakers are making some progress. Metalclad switchgear is popular in Great Britain, but on the Continent and in America it is by no means as widely employed. This metalclad gear is usually characterized by draw-out type switches in which the latter may be disconnected from the bus-bar chambers through plugs and sockets. Flash-overs and tracking may take place on the insulation of these parts unless they are properly maintained; that is to say, they must be kept free from dirt and moisture. With all switchgear, however, mechanical troubles constitute a large proportion of those arising in service and their diagnosis is usually straightforward. Amongst electrical faults, if exception is made of catastrophes due to switches being incapable of handling the fault current, one of the most common sources of failure is in the auxiliary circuits. Apart from periodic examination and testing, it is very desirable that these parts should be readily accessible so that trouble can be rectified quickly, should it occur.

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